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MAGMAS AND ORES.[1]

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I WISH to consider briefly the development of ideas regarding magmatic mineral deposits, to note whither they trend, and whether they accord with recent field and microscopic work. Also, I wish to approach them from the viewpoint of the field economic geologist, and not that of the petrologist and geochemist, for whose work my respect is greater than my knowledge.

When Hutton's concept of a molten injection of sulphidic ores became untenable against the growing inconsistencies of field observations, there was a pronounced swing of thought away from a magmatic origin of ores. Nevertheless, a firm foundation for a magmatic origin of certain ores had been laid by Hutton's concept of igneous rocks. It is true that this idea had been entertained earlier, but in a very vague form. It is also true that the ores Hutton conceived to be molten injections are now believed to have originated from aqueous liquid solutions. The idea that some ores are merely unusual varieties of igneous rocks had not yet gained a foothold.

Early Nineteenth Century thought veered away from the molten injection idea of Hutton, and from the low-temperature Neptunistic views of Werner. A reversion to the pre-Werner ideas of Descartes took place, and there emerged a fusion of the two schools of thought in which waters and vapors were considered to be ore-carrying agents, but that these were of magmatic deriva-

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tion. Such ideas were expressed by Breislak in 1811, by Scrope in 1825, by Fournet in 1834, by Scheerer in 1847, and notably by the illustrious DeBeaumont in 1847. These views slowly gained recognition throughout the Nineteenth Century until today, waters and vapors have become almost universally accepted as the causative agents of most epigenetic ore deposits. Recent writings, such as the extended treatise of Graton on The Nature of the Ore-Forming Fluid, assume, without argument, a magmatic derivation of the metallizing solutions, and are concerned with the chemical character and means of egress of the solutions from the magma. These fugitive magmatic emanations, and whether they are alkaline or acid, or escaped in a gaseous or in a liquid state, are matters of no concern of this paper. Neither are the varied types of mineral deposits that have resulted from their upward passage through the rocks. It is to the ore-forming processes coincident with the crystallization of the magma that I wish to direct attention.

Fournet in 1845 and 1856, on the basis of extended field observations, reverted to the Hutton concept that ore veins were magma injections rather than depositions from aqueous solutions, but the crustified sulphide veins he cited as examples rightly failed to convince his contemporaries. DeBeaumont (1847), however, although the premier proponent of magmatic emanations, clearly recognized that deposits of magnetite, chromite, and platinum were formed as segregations in igneous rocks as a result of crystallization during cooling of the intrusive. Others had vaguely expressed this view, but DeBeaumont's appears to have been the first clean-cut statement of magmatic segregation. This concept lay dormant during most of the remainder of the 19th century, perhaps because the eminent and critical von Cotta in his careful survey of preceding theories of ore genesis (Erzlagerstätten 1859, and Prime's translation 1879) moderately but effectively marshalled arguments against magmatic injections in general. This concept must have been depressed further by the opposition that arose to Belts' proposed quartz-magma or ore-magma (1861, 1874), and it was lost sight of during the hectic controversy over the lateral secretion origin of veins.

Sjögren, Törnebohm, and Igelström demonstrated a magmatic origin for the oxide ore deposits of Taberg, but it took the judicial mind of J. H. L. Vogt, supported by a sound knowledge of physical chemistry, to resurrect magmatic segregation from an hypothesis to a substantial theory, and his contributions marked an epoch in the history of the development of magmatic ore concepts.

Vogt had become a student of the newly developed science of physical chemistry, and in 1891 and 1892 published his first papers on the formation of magmatic segregations of ilmenite, titaniferous magnetite, chromite, and nickeliferous pyrrhotite, by differentiation of basic magmas. These were later embodied in the oft-quoted, notable paper, published in the initial number (1893) of the Zeitschrift für Praktische Geologie. Vogt showed that the oxide ore minerals are common accessory minerals of basic igneous rocks, and gradually increase with respect to the silicates to form aggregated concentrations of ore minerals. He considered, however, that the oxides crystallized before the silicates, but that the sulphides were later. Knopf states that the principle of a magma being a solution was first introduced by Bunsen in 1861, and developed by Lagorio in 1887, but Vogt's writings of the early Twentieth Century firmly established how the laws of solutions are applied to magmas, and how differentiation proceeds to yield magmatic segregations. Vogt's studies of slags applied to igneous rocks later led to his important finding that sulphides separate as a liquid phase from basic magmas, and remain molten after the silicates have crystallized. This thin, sulphidic liquid phase either segregated in the lower parts of the magma chambers, or became injected into the frozen mother rock or the invaded rocks.

Vogt's early conception of the mechanism of differentiation by which the oxide ores became segregated was naturally rather vague. He considered that they crystallized and aggregated in the solid state, or became concentrated through diffusion in the liquid state. After the appearance of Schweig's pioneer work of 1903, which based magmatic differentiation upon crystal settling, and the remelting of the sunken crystals in the hotter depths, Vogt referred to it as an interesting paper and adopted this mechanism

in explanation of magmatic segregations and injections. Crystal settling was the means by which magnetite became separated out of the magna and underwent concentration, and remelting or partial resorption, as Vogt termed it, was the means he conceived for supplying a fluid magnetite magma available for injection. Vogt was deeply interested in the magnetite deposits of Kiruna. He often remarked upon the observed intrusive relations of the magnetite to the overlying and underlying rocks. He was forced to the conclusion, therefore, as was Stutzer and Geijer, that the Kiruna magnetite was emplaced by the injection of a body of molten magnetite of high purity. To account for the fluidity of a body of magnetite that had accumulated by the settling of solid crystals, he adhered to Schweig's original idea of remelting, or resorption. This adherence was helped, no doubt, by his early concept of a thin, fluid, sulphidic magma, which at that time appeared to account so satisfactorily for the field associations of the Norwegian nickeliferous pyrrhotite deposits.

Elsewhere, such petrologists as Harker, Daly, and Niggli, had accepted Schweig's hypothesis of differentiation as applied to igneous rocks, and elaborated upon it. That part of it relating to differentiation by crystal separation was ardently taken up by Bowen whose epoch-making monograph in 1915 on the *Late Stages in the Evolution of the Igneous Rocks,* with its able reasoning, and experimental and field evidence, compelled assent by most geologists to the dominant role of gravitative crystallization in differentiation. In fact, many students assume that "Bowen's theory," and differentiation are synonymous. When Bowen later added to crystallization-differentiation the process of squeezing off or filtering out the residual liquid at any stage (filter-pressing), and his reaction principle, crystallization-differentiation commanded almost universal acceptance. Vogt adopted it immediately as the mechanism of separation, but still adhered to the remelting of sunken crystals. Only in the last few years has there been active dissent against the universal application of crystallization-differentiation, headed by Fenner and Holmes.

During the period of the general adoption of the theory of gravitative crystallization-differentiation, the reflecting microscope for the study of opaque ores was coming into use by economic geologists. They also were actively studying so-called magmatic segregations in the light of crystallization-differentiation. Many of them had become aware that the oxide and sulphide ore minerals of supposed magmatic deposits are later than the silicate rock minerals. This came to be explained, in the case of supposed magmatic sulphide ores, by Vogt's idea of the lower melting points of sulphides, whereby they remained liquid after the consolidation of the silicates. This was the explanation adopted in 1917 by myself for the Sudbury deposits.

Microscopic examination of ores was revealing that many supposed early magmatic minerals were later than the silicates. These prevailing ideas and growing lists of occurrences of late magmatic ores were assembled by Tolman and Rogers in 1916, and their work sharpened the realization of the commonness of late sulphide, and some oxide, minerals. They, however, claimed that the sulphides were late magmatic but their proofs have been interpreted by others as indicating only high-temperature hydrothermal origin. The controversy that arose from their example of the Engels, California, sulphide ores as late magmatic, died naturally when Knopf and Anderson showed that three periods of intrusions separated the ores from their supposed mother rock. Similarly, the work of geologists of the International Nickel Company at Sudbury, Ontario, have revealed successive intrusions between the consolidation of the norite and the formation of the nickel-copper ores. Their evidence so far favors a hydrothermal rather than a magmatic origin for the Creighton type of ore at least.

The magmatic oxide occurrences, however, were offering stumbling blocks, since the oxide minerals were presumed to have settled out as early-formed crystals giving rise to ore segregations. The reflecting microscope, however, was revealing that most magmatic oxides, like the sulphides, are later than the silicates. This obviously is inconsistent with accumulation by early crystal set-

tling. Moreover, some of the magmatic oxide "segregations," particularly marginal and central "segregations," also seemed inconsistent with an origin by the generally accepted normal process of gravitative crystallization-differentiation.

It had been growing upon me for some time that what was then most needed was further field evidence, and detailed re-examination of some of the oxide "segregation" deposits to see if they really were segregations, and if so how they had been formed. The marginal segregations seemed puzzling, and the central segregations enigmas. The titaniferous-magnetite deposits of the Adirondack region were selected for restudy because, since the work of Kemp in 1897, these had been considered as typical "segregations" in anorthosite and gabbro. This work was undertaken in 1926–27 by F. F. Osborne who found that they are injections and not segregations—an advisable distinction—and are either discordant or concordant with the primary structure of the host rock. He found the oxide ore minerals to be definitely later than the silicates and, therefore, ruled out magmatic segregation by the sinking of early-formed crystals. The deposits were concluded to have resulted from the injection of a titaniferous magnetite residual-magma, filter-pressed from a mush of plagioclase crystals. These type examples of early-magmatic *segregations* thus became late-magmatic *injections*. Similarly, the supposed magnetite segregations of Lyon Mountain, New York, were found by Gallagher, in another phase of this investigation, not to be segregations, nor even late-magmatic, and this was also found to be true of the supposed magnetite segregations near Dover, New Jersey.

Elsewhere many other segregations of magnetite have been shown to be late-magmatic injections, or non-magmatic. The injected nature of Kiirunavaara has already been mentioned, although a pneumatolitic origin has also been suggested for it and other iron deposits centering around Kiruna. At Taberg, the oxide ores are later than the silicates. Loewinson-Lessing, Duparc, and Zavaritsky have pointed out that the magnetite of Goroblagodat, and of some other Ural deposits, is later than the rock silicates, and came in as a liquid in which feldspars and rock

fragments floated. The large titaniferous magnetite bodies of Iron Mountain, Wyoming, are late magmatic segregations or injections. The extended Bushveld titaniferous-magnetite bands were first considered by Hall and Wagner to be early gravitative crystal settlings, but it was later shown by Hall, and by Lombaard, in the publications of the Geological Survey of the Union of South Africa that the magnetite crystallized after the rock silicates. Polished and thin sections from a suite collected across the Magnet Height bands of the Bushveld in 1929, show that the magnetic oxides wrap around, enclose, and corrode the feldspar crystals, and clearly were fluid after the crystallization of plagioclase, bronzite, and pyroxene. Singewald and many others have pointed out similar instances.

Many other illustrations could be drawn, but the above suffice to show that the magnetic oxides of magmatic iron deposits crystallized from a fluid that was liquid until after the crystallization of the host-rock silicates.

In the case of chromite the evidence is not so one-sided. Formerly all chromite deposits were considered to be early accumulations of settled crystals. Field and microscopic evidence testify that in many places this is indubitably the case. However, Sampson, Ross, Singewald, Fisher, and others cite evidence of some late magmatic chromite. The chromites of the Bushveld Complex in part are of early crystallization, and in part are later than some of the silicates. Sampson concluded that the striking Dwars River chromitite occurrence of the Bushveld represents an intrusion of chromite-rich residual magma, a conclusion later concurred in by Hall. My own observations, and thin and polished ore sections confirm this. Chromite, then, in part appears to be early magmatic and in part late magmatic.

Platinum, another metal of magmatic origin, also appears to have crystallized late in the magmatic stages. Duparc (Gites Platinifères de L'Oural et du Monde, with Tikonowitch, Geneva, 1920) shows that in the Urals, the platinum occurs in a central differentiate of dunite, which is surrounded by successive envelopes of pyroxenite and gabbro. It occurs alone or with chromite, moulded against or around the silicates. Of the South African

occurrences, Wagner (Platinum Deposits, 1929) states that the Merensky Reef type occurs with the sulphides, which crystallized later than the silicates, and that the hortonolite-dunite type represents a late magmatic fraction; this is also confirmed by a microscopic study of polished specimens.

This brief review indicates that there are several modes of occurrence and origin of magmatic deposits, which facts in part are responsible for the confusion and controversies found in the literature. "Magmatic segregation" has often been assumed to be the only type of magmatic deposit; early and late magmatic too often have not been distinguished. As a result, some writers have considered that certain deposits could not be magmatic simply because they are not segregations, or because ore minerals later in age than accompanying rock silicates precluded separation by early crystallization. Unnecessary conflict of interpretation arose and still exists. Some of this confusion need not occur if it is realized that there can be more than one period of ore formation within the strictly magmatic period, and that there may be more than one process of differentiation by which magmatic deposits may result.

In an attempt to clarify this matter I propose the following simple classification of magmatic deposits, and of the processes that gave rise to them, retaining familiar terminology.

CLASSIFICATION OF MAGMATIC MINERAL DEPOSITS AND PROCESSES.

Type.	*Process.*	*Examples.*
I. EARLY-MAGMATIC		
A. Dissemination	Disseminated crystallization without concentration	Diamond pipes; some corundum deposits
B. Segregation	Crystallization differentiation and accumulation	Bushveld chromite
C. Injection	Differentiation and injection	Kiruna, Sweden(?)
II. LATE-MAGMATIC		
A. Residual liquid segregation	Crystallization differentiation and residual-magma accumulation	Bushveld titanomagnetite; Taberg(?); Iron Mt., Wyo.(?); Bushveld platinum
B. Residual liquid injection	Same, with filter pressing, and. or, injection	Adirondack magnetite, Kiruna, Sweden(?) Pegmatites
C. Immiscible liquid segregation	Immiscible liquid separation and accumulation	Insizwa, Africa
D. Immiscible liquid injection	Same, with injection	Vlackfontein, Bushveld, S. Africa

The *Early-Magmatic* group includes deposits formed during the main stages of magma crystallization, and embraces those that have been termed orthomagmatic and orthotectic. The *Dissemination* deposits have resulted from simple crystallization *in situ* without concentration, and are represented by deposits of diamonds, pyrope, and by some types of corundum deposits. The *Segregations* are accumulations of early-formed crystals, either gravitative, or constrictional flowage as explained by Balk. They are represented by numerous chromite deposits. This group formerly would have included most magmatic deposits of magnetite, ilmenite, platinum, and nickel-copper sulphides, which now, however, must be considered as late magmatic. Few new deposits have been added to this class. Many have been removed, and few remain. Early-magmatic *Injections* include deposits that are igneous injections, which presumably are earlier than, or contemporaneous with, associated pyrogenic silicates. Representatives tentatively assigned to this group are the Kiruna magnetite deposit, and the Cumberland, Rhode Island magnetite dike. They are assumed to be magmatic differentiates, which raises the problem of how, or if, an early magmatic liquid differentiate can form. If early crystals were remelted, as Vogt maintained, would it be early-magmatic? If immiscible-liquid separation of oxides is impossible, and remelting cannot occur, then it may prove that deposits assigned to this class are really late-magmatic injections derived from undisclosed sources, and that there are no representatives of early-magmatic injections.

The *Late-Magmatic*[2] group includes deposits of pyrogenic minerals that have crystallized toward the close of the magmatic period. They are consolidated residual-magmas. Consequently, the ore minerals as individuals, or in deposits as a whole, are later than the rock silicates, cut across them, embay them, and react with them. Contained volatiles released upon consolidation may alter the enclosing silicates, and produce some effects of hydrothermal solutions. They are associates of basic igneous rocks,

[2] Late-magmatic is here used to designate deposits formed by crystallization during the late stages of consolidation, and does not include, in the sense of some writers, deposits that result from magmatic after effects.

and have resulted from variations of crystallization-differentiation, liquid immiscibility, or other modes of differentiation. Most of the magmatic deposits may now be considered to fall within this group.

The two *residual liquid classes* are liquid residues of consolidation, which drain out, are squeezed out, or otherwise segregate from the crystal interstices within the consolidating magma, and there crystallize as the last pyrogenic minerals, to form late-magmatic segregations. Or, the residual liquid may be squeezed out to form late magmatic injections. Representatives of late-magmatic segregations would be the Bushveld titanomagnetite bands, platinum deposits, and perhaps Taberg, and Iron Mountain, Wyoming. Examples of late-magmatic injections would be the Adirondack titaniferous magnetites, and perhaps Kiruna. The *immiscible liquids* accumulate toward the bottom of the magma chambers where, under stable crustal conditions, they may consolidate later than the rock silicates, forming *immiscible liquid segregations,* or under crustal disturbance they may be squirted out to form *immiscible liquid injections* that penetrate the host or enclosing rocks. Scholtz shows that Insizwa, South Africa, would belong to the segregation class, and Schwellnus that Vlackfontein, South Africa, would be an example of the injected class. Perhaps also the Frood deposit of Sudbury may come to be considered as belonging to this class.

In proposing this classification I hope it may prove to clarify the various magmatic processes, and permit distinctions not only between the operation of early- and late-magmatic processes, but also between magmatic accumulations that have remained quiescent to form one type of deposit, and those that have been injected to form another, and controversial, type.

I should like to turn now to the late-magmatic oxide deposits, and preface this by stating that abstract reasoning should not be used as a substitute for field and microscopic studies. The instances cited previously, demonstrate that economic geologists have adduced field and microscopic evidence to show that deposits of magnetic oxides in particular have crystallized later than

the silicates of basic igneous rocks. Petrographic examinations of basalts and diabases have likewise shown that a magnetite-rich fluid has remained liquid after the crystallization of the feldspars and pyroxenes, and crystallized in their interstices. This has been demonstrated by Washington, Newton and Teall, and by Fenner, who assembled a number of such instances in 1929, 1931, and 1937. Only last year Walker, in a bulletin of this Society, also showed that magnetite is a late constituent of the Palisade diabase and is richest in the pegmatitic schlieren, which represent the latest crystallization.

The late magnetic oxides have been accounted for by liquid immiscibility, remelting of sunken crystals, and by being an interstitial residual magma. Liquid immiscibility as formerly advocated by Lindgren and others has been generally objected to by petrologists who agree that the iron oxide and silicate constituents of a magma are miscible in all proportions. The remelting of early-formed magnetite crystals, as later advocated by Vogt and Lindgren, has been objected to by Bowen on the basis of insufficient temperature to remelt magnetite, and further that to obtain remelting, the high temperature required would also melt the surrounding silicates, and miscibility would ensue. Perhaps our knowledge may not be sufficient to dismiss the possibility of remelting of sunken crystals. Certainly, laboratory experience is inadequate, because the high melting point of pure magnetite or ilmenite may not be that of titano-magnetites with associated silicate melt and unknown fluxes, volatiles, or mineralizers. One thing, however, seems definitely known, namely that magnetite-rich liquid existed after the crystallization of silicates.

The accumulation of magnetic oxides in a residual magma seems inescapable. There is the testimony of magnetite as an interstitial crystallization in basalts and diabases as shown by Newton and Teall, Washington, Fenner, Newhouse, Walker, and others. There is the testimony of injected bodies of magnetite such as described by Osborne for the titaniferous-magnetite deposits in the Adirondacks. There is the testimony of Bushveld titanomagnetite that surrounds sparse plagioclase phenocrysts, or

forms a groundmass for aggregated plagioclase and pyroxene crystals. Fenner has argued in the American Journal of Science in 1929, in the Mineralogical Magazine in 1931, and again in the Journal of Geology in 1937, that the residual magnetite disclosed in some basalts and diabases is opposed to differentiation solely by the theory of normal gravitative crystallization-differentiation as advanced by Bowen, which postulates a more silicic residue. This, however, has not gone unchallenged by Bowen.

A residual magma rich in titaniferous magnetite is not what should be expected under normal crystallization-differentiation. Yet it apparently has formed. We must conclude, therefore, that *normal* crystallization-differentiation does not operate in the cases of those basic magmas that give rise to magnetic oxide deposits. In the case of deposits associated with anorthosites, such as those of the Adirondacks, plagioclase and pyroxene crystallized first, and magnetite with or without pyroxene formed a residual magma, which Osborne considered was filter-pressed from the plagioclase interstices. In the case of deposits associated with rocks containing olivine, the explanation is not so simple since some magnetite also contains olivine, a mineral that generally crystallizes early. In the platinum pipes of the Bushveld, however, magnetite and ilmenite crystallized later than the olivine. Thus, magmatic iron oxide deposits also appear to oppose the universality of the present concept of normal gravitative crystallization-differentiation as applied to all types of basic igneous rocks.

Perhaps there has been too much blind following of the Rosenbusch order of crystallization established for silicic rocks. The field and microscopic evidence indicates an apparent reversal of this order for certain types of basic magmas rich in iron and titanium. If, under certain circumstances, plagioclase and pyroxene crystallize first and iron oxides later, an adequate explanation is provided not only for many common ore occurrences, but also for many complex ore associations, stratiform banding, and conflicting opinions. Further consideration of liquid immiscibility of iron oxides and silicates would no longer be necessary, and the complications of remelting of sunken crystals would be avoided.

If this were the explanation, then the iron-rich residual magma could assume several positions and forms, and account for many varied field occurrences. It might crystallize in the interstices of the silicates giving, if in small quantity, the features of basalts and diabases previously referred to; if in larger quantity it would give rise to low-grade disseminated magnetite ores. If it were abundant, various types of ore deposits might conceivably result. The iron-rich residual fluid might drain out from among marginal, clustering silicate crystals, and collect as a liquid in a central unconsolidated part of the magma chamber, where under quiescent crystallization, late-magmatic segregations would result. The iron-rich residual liquid might trickle downward through upward-rising clusters of silicate crystals, and collect as a liquid bottom-layer or stratum, as in the Bushveld. Growing plates of plagioclase would pop to the top of this heavy liquid layer, and jammed against preceding ones, like wooden shingles on a water surface, would give rise to pseudo-stratification. As the heavy liquid itself cooled, laggard plagioclase crystals would be trapped as isolated inclusions. Here may be the explanation, as hinted by Hall, of the Bushveld stratiform bands of titanomagnetite, with sparse plagioclase plates in the lower part, numerous ones higher up, and overlain by a pseudo-stratified rock composed of closely packed plagioclase plates whose greater axes parallel the magnetite bands, and whose interstices are occupied by minor magnetic oxides. Alternatively, the oxide-rich liquid may have so accumulated in some depression from which it became spilled by slow tilting into its present position on an already solidified anorthosite floor.

Under conditions of concomitant disturbance, such accumulations of still liquid, iron-rich, residual magma, might be squirted out into overlying consolidated portions of the mother rock, or into the enclosing rocks, giving rise to late-magmatic injections such as those of the Adirondack region, and perhaps Kiruna. Or, if late liquid accumulation had not occurred, interstitial magnetite-rich fluid might be filter-pressed out to form injections, such as Osborne considers for the Adirondack injections. Thus, late-magmatic oxide injections might be explained. If the iron-rich

residuum should be high in volatiles, it might escape from the magma chamber to form high-temperature, non-magmatic deposits of magnetite, such as those of Lyon Mountain, New York, or Dover, New Jersey.

The very simplicity of these suggested methods of formation of magnetic oxide deposits naturally raises suspicion as to their probability. You will note that the ideas are not entirely new; the newness is in their extension to the formation of all late-magmatic iron deposits of economic size. Separation is by crystallization, and accumulation is gravitative, and it is, therefore, a variation of crystallization-differentiation but it is gravitative accumulation of a heavy residual liquid rather than settling of early-formed crystals. It is liquid gravitative differentiation.

Now, what about the various "ifs" that have cropped up? Does field and microscopic evidence justify consideration of a residual magma rich enough in iron to form deposits? It is a fact that late magnetite-rich residues occupy interstices of silicates in basalts, but these are not iron deposits. It likewise is a fact that magnetic oxides in large masses completely enclose plagioclase and pyroxene crystals but this only proves that the iron oxides are later than the silicates, and it is only an assumption that they may have been part of a rest magma. Contrarywise, dominant opinion is that crystallization proceeds toward a silicic residual magma, and this concept is not questioned in respect to many basic magmas. However, has not *normal* gravitative crystallization-differentiation been adhered to too blindly, and is it not also an assumption to consider that it holds for all basic magmas. Fenner pointed out in 1931 that the Bowen-Schairer-Williams diagrams of the system Na_2SiO_3-Fe_2O_3-SiO_2 shows that in one case the final product may contain iron oxide. Newhouse's microscopic study shows that in some basic rocks magnetite is earlier than the silicates, but that in others it is later. There is thus a difference in the time of crystallization of magnetite, which apparently depends upon the nature of the magma, giving early magnetite in some cases and late magnetite in others.

I suggest, therefore, the possibility that in certain types of iron-titanium-rich magmas, differentiation, perhaps influenced by vola-

tiles and strong fluxes, results in an iron-rich residual magma that may give rise to such types of magmatic iron deposits as the Adirondack, Iron Mountain, Taberg, the Bushveld, perhaps Kiirunavaara, and also to platinum pipes and some chromite deposits. One cannot state that laboratory evidence opposes it, since laboratory evidence is too incomplete; equilibrium diagrams after all are not natural magmas. Also, there is little laboratory evidence to support it. On the other hand it does accord with field and microscopic observations. I offer it as a possibility for further exploration.

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YALE UNIVERSITY,
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NEW FRONTIERS IN MICROPALEONTOLOGY.

With Especial Reference to Petroleum Exploration.

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ABSTRACT.

This paper surveys the new frontiers in micropaleontology with especial reference to their possible contribution to petroleum exploration, and emphasizes those groups of microfossils which have not yet received the attention their presumed economic potentialities suggest they merit. In this category belong protozoans other than foraminifera, microscopic plant remains such as sillicoflagellates, coccoliths, discoasterids, and spores and pollen, as well as fragments, dissociated parts, or growth stages of typically megascopic fossils, such as crinoids, holothurians, bryozoans, worms, trilobites, and so forth.

The microfossils potentially useful in the search for petroleum are discussed in the light of the thesis that in the future micropaleontologic studies should contribute not alone to the routine identification of horizons penetrated by the drill, as at present, but to the solution of some of the more obscure, yet vitally important, geological problems concerning oil and gas, such as the evaluation of the roles of the organic, paleogeographical, sedimentological, stratigraphical, and structural factors in the origin and localization of these hydrocarbons.

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[1] Paper presented at the 50th Anniversary Celebration, University of Chicago, September 26, 1941, as a part of the symposium, Geological Frontiers in the Search for Oil.

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GENERAL INTRODUCTION.

TODAY, even as we examine New Frontiers in Geology, the British Association for the Advancement of Science, meeting in London, opens its symposium on "Science and the World Order." The English discussions are dedicated to the solution of the problem of how mankind can be persuaded to desist using, as destructive weapons, the instruments growing out of, or the materials made available through, scientific endeavor. Another question which they hope to answer at that symposium is: "What now are the rights and duties of scientific men?" Whatever the British scholars, meeting in a city which has suffered grievously from the misuse of scientific knowledge, decide concerning these "rights and duties," at *this* symposium there probably is general agreement that one of our chief duties is to continue to seek *new frontiers.*

Some of our English scientific cousins may well think that in a world which does not even have the distinction of being "harmoniously confused," symposia devoted to scientific advances in the "peaceful arts" are mere trivia. But even should our planet be wholly ruled by men whose heads, as Shakespeare said, "do

grow beneath their shoulders," nevertheless as scientists we should still have to

> See beyond barbaric steel . . . the bigot's bitter zeal,
> And all the garbled fury of our age.

Inasmuch as it is inconceivable to think of either the present or the postwar world, however good, or bad, without an increasing need for petroleum products, it is with both academic acumen and financial foresight that we try to explore frontiers in petroleum geology. You need not take a geologist's word for this inasmuch as the Dean of St. John's College, Scott Buchanan, who has been an arch-advocate of the world's hundred greatest books as the *ne plus ultra* of all collegiate education, now suggests that *liberal arts* colleges conduct courses in the theory, operation, maintenance and repair of gasoline engines, stating that such courses would contribute experts "to the culture of the country which is and will be more and more a culture on wheels." With such a recommendation, the future of petroleum geology seems secure.

Because we are talking about frontiers, perhaps at this point it should be decided what is meant by the word. As early as 1523, the term frontier was employed to designate the "front line or foremost part of an army," hence that portion whose duty is to attack. This meaning is appropriate to usage of the word in these symposia because, however fûtile our own personal efforts, we all like to think of ourselves as being in the attacking portion of the scientific army. But the preferred definition for frontier is "that part of a country which fronts or faces another country." This also is particularly *a propos* to our purposes, for some of the most fertile frontiers of our geological fatherland are those that merge—not without many a border incident—into the frontiers of a number of other scientific domains.

KINDS OF FRONTIERS IN MICROPALEONTOLOGY.

It is obvious that few scientists can be on the outer limits of the geological frontier. Moreover there is no guarantee that because a worker is on the frontier today he will be there tomorrow, for yesterday's trackless scientific frontiers are crisscrossed by to-

day's technical highroads. In order to explore successfully the peripheral areas of any science, however, the highways by which the borderland may be reached must become familiar avenues. Thus before discussing frontiers in micropaleontology, the background of the subject should be thoroughly explored. But inasmuch as this topic has been recently reviewed,[2] it will be touched upon as little as possible in this paper.

The new frontiers in micropaleontology are traversed by trails that extend in several directions. One of these paths leads toward chiefly "academic" results—results, for instance, which may have far-reaching importance in determining the interrelationships and evolutionary development of some groups of as yet incompletely known invertebrate fossils. Explorations in this direction obviously are not likely to yield short-term economic rewards, nevertheless it must be remembered that even the most abstruse academic subject, such as the ontogeny of the foraminifera, has a miraculous way eventually of turning out to have a concrete financial application.

"ACADEMIC" FRONTIERS.

Commonly investigations of the "ultra academic" type are inaugurated as by-products of more routine micropaleontologic studies. Such, at least, in large part is the history of the expanding inquiry into the Allagecrinidae, or microscopic crinoids. It is also the background of the investigations on the microscopic growth stages of blastoids,[3] and the studies of echinoderm pedicellariae[4] carried on in our laboratories, for both of these "academic" inquiries are off-shoots from ostracode researches which are not without their direct economic applicability.

Still other investigations that fall into this "academic" category are the presently all too little pursued quantitative and statistical paleontologic studies, the scientific background for which

[2] Croneis, Carey, Micropaleontology—past and future. Bull. A. A. P. G., 25: 1208–55, 1941.

[3] Croneis, Carey, and Geis, H. L., Ontogeny of the Blastoidea. Jour. Paleon., 14: 345–355, 1940.

[4] Geis, H. L., Recent and fossil Pedicellariae. Jour. Paleon., 10: 427–448, 1936.

may be acquired by a careful examination of Simpson and Roe's "Quantitative Zoology."[5] The limited amount of work already done in this legitimate and potentially promising micropaleontologic field has yielded results that should encourage many more students to enter it. For instance, graphical studies of fossils pursued chiefly with a view toward determining variations should yield not only important information concerning the mechanics of evolution but data also of potential economic significance. Many English and continental workers, therefore, have been interested in some phases of this work, but few American students have invaded the field, the essential features of which can be gleaned from the last two addresses of H. H. Swinnerton[6] before the Geological Society of London, or by the perusal of certain chapters in the "New Systematics" of Julian Huxley and associates.[7] Inasmuch as the American workers have lagged behind their European cousins in these research subjects, and particularly because the work already accomplished has been largely predicated on megascopic fossils, the micropaleontologic opportunities seem particularly promising on this frontier. Moreover, of all the relatively abstruse "academic" researches, these paradoxically may have the greatest commercial potentialities, especially in the search for new stratigraphic traps for oil.

Another, and a very recent example of the entirely "academic" type of paleontologic investigation is Whitehouse's discovery and description of two species of semi-microscopic, unattached, echinoderms in the lower portion of the Middle Cambrian of Queensland, Australia.[8] One of these echinoderms, *Peridionites,* is bilaterally symmetrical and corresponds remarkably well with the hypothetical *Dipleurula,* although in some respects it may be even more primitive. The other echinoderm, *Cymbionites,* is radially symmetrical and resembles the free pentactula stage in the ontog-

[5] Simpson, G. G., and Roe, Anne, Quantitative Zoology. 1939.

[6] Swinnerton, H. H., Paleontology and the mechanics of evolution. Q. J. G. S., XCV: xxxiii et seq., 1939. ——, The study of variation in fossils. Q. J. G. S., XCVI: lxxvii et seq., 1940.

[7] Huxley, Julian, et al., New Systematics. Oxford University Press, 1939.

[8] Whitehouse, F. W., Early Cambrian Echinoderms similar to the larval states of recent forms. Memoirs Queensland Museum, 12: Part 1, 1–28, 1941.

eny of the eleutherozoic echinoderms. The morphological correspondence of these two early forms with the two chief larval stages of the modern echinoderms makes unnecessary the attached stage in the ancestry of the Eleutherozoa which has been pretty generally considered requisite heretofore.

Here then is a perfect instance of the important results that may be obtained by a careful search for, and a still more detailed scrutiny of, the less familiar smaller fossils in any stratum—fossils that commonly pass unnoticed and, if seen, remain unstudied. It cannot for a moment be maintained that this discovery, important as it is scientifically, has at present any bearing whatsoever on the problem of discovering oil; but nevertheless critics would find it difficult to prove that Whitehouse's significant "academic" researches cannot possibly have any future bearing on petroleum geology. Moreover, all such studies demonstrate the good results that can be obtained by having paleontological frontiersmen serve as guides to biological explorers less familiar with rocky terrain.

"COMMERCIAL" FRONTIERS.

The much more beaten paths on the micropaleontological frontier are travelled by those workers involved in the seemingly rather routine processes of increasing knowledge regarding the distribution, range, and ecological features of the commonly employed "commercial" micropaleontologic groups, or in discovering new ones that may also have some utility in subsurface diagnosis. In the future, such investigations increasingly will require that the micropaleontologist not alone poke beneath the surface of the earth, but prod beneath the waters of the sea. Moreover, he will have to reexamine some of the liquids of the earth's crust. Briefly to cite examples, the micropaleontology of the ocean bottom is now in its infancy. But with the further development of sampling devices, such as the Piggot gun, rich scientific results, with potential commercial applicability, may be expected from this field. The liquids of the earth's crust must be considered, for it is obvious that the micropaleontology of the oil field waters should be extensively reexamined. Moreover, the oils themselves should be the

objective in another campaign, using some variation of Sander's method of attack.[9] In our own laboratories we have been experimenting with such variations with some promise of success in increasing the speed and efficiency of separation of organic remains from the crude oils. More efficient water soluble filters must be devised, however, and the gold size now commonly employed to entrap the remains during centrifuging must be improved or substituted for. This line of micropaleontologic investigation is particularly important because it appears not unlikely that the key to the solution of the problem of the origin of oil may be found in the very microscopic remains entombed in it. Naturally the contamination hurdle involved in such investigations is a difficult one to clear. But were this not so, these would not longer be frontier subjects.

Definitely Economic Frontiers. This major type of micropaleontologic borderland has several investigational sub-provinces, of which two have significance for us. Prominent in the past have been the researches of the first sub-province. These have been conducted largely, but far from entirely, in the petroleum industry. They are avowedly economic in type for they are designed *solely* to establish the validity or increase the value of certain groups as stratigraphic markers, or to increase the speed of stratigraphic diagnosis in petroleum geology. The importance of this research sub-province should not be minimized. Nevertheless it must be remembered that using a few "marker" foraminifera, an expert micropaleontologist of the Gulf Coast may examine daily as many as a hundred samples and log from three to four thousand feet of section. Even in California, where some consider it necessary to identify approximately 100 species in each sample, it is stated that expert workers average not more than 20 minutes per sample. It does not seem likely, therefore, that much greater speed can be acquired or is absolutely necessary. But new "markers" can be found, and new groups exploited in providing potential index fossils. Such researches will always be impor-

[9] Sanders, J. McConnell, The microscopical examination of crude petroleum. Jour. Inst. Techn., London, 23: 525–573, 1937.

tant, for, despite the increased activity in electrical logging, and the introduction of logging through the use of radioactivity, the *key* stratigraphic determinations in the search for petroleum probably will continue to be obtained through micropaleontologic or micromineralogic methods.

Potentially Economic Frontiers. Too little explored in the past but, we may hope, to attract increasing numbers of micropaleontologic frontiersmen, is the second research sub-province, which is open to both academic and commercial travellers. This province, which lies closest to the "academic," contains problems more fundamental to stratigraphy and paleontology than the mere setting of casing, important as such a problem may be. Investigations in this research area possibly may not bear commercial fruit for a number of years. Some studies, indeed, may be entirely barren commercially. But over a period of years most investigations of this relatively "pure research" type will not only be scientifically productive, but in one way or another they will likely prove to have more than paid their way financially. More of such "potentially economic" researches should be in progress, and they should be supported more adequately by commercial concerns, whether the work is carried on in university laboratories, by state or Federal surveys, or by the companies themselves.

FORAMINIFERA.

Investigations in stratigraphic diagnoses, which comprise the great bulk of economic micropaleontologic researches, cannot be discussed in detail here. Most of the work, however, still revolves almost entirely around the foraminifera. But despite the almost incredibly large research output in this field, much remains to be done, especially in the utilization of new biological data in the solution of problems of economic geology.

Fusulinids. Some of the detailed work on foraminifera of the fusulinid group locally has also proven of major economic significance, but the number of workers is limited as is the geological range of the fossils. Both academic and petroleum paleontologists have contributed heavily to this sub-field whose theoretical impli-

cations eventually may well prove more important than its direct utilitarian value in stratigraphy.

Arenaceous Foraminifera. Another foraminiferal division which promises to be of increasing importance is the so-called arenaceous type. Arenaceous foraminifera are abundant in many rocks that are entirely or essentially devoid of other diagnostic fossils. They should be studied in far greater detail and by many more workers than has hitherto been the case. Fortunately, during the last 10 years there has been a gratifying upsurge of interest in this group. Their study requires the perfection of a delicate technique in the acid reduction of limestones carrying the insoluble but rather easily destroyed remains. Workers in this country already include Dunn, Howell, Kjellesvig, Moreman, Shrock, and others. In Europe the researches of Eisenack,[10] especially on the arenaceous foraminifers of the Silurian beds of the Baltic region, not only have demonstrated forcibly what splendid results can be expected from such investigations, but in addition they prove that the micropaleontological by-products that commonly result from such studies may be equally important. The almost unbelievable microscopic remains which Eisenack has discovered in the Ordovician as well as Silurian strata of the Baltic area, and the Bohemian basin should whet the interest of all American workers in the micropaleontology of the Paleozoic rocks. Moreover, the technique of removing essentially unaltered organic remains from siliceous rocks by the use of hydrofluoric acid, as practised by Eisenack, should be perfected in this country.

The subject of early Paleozoic arenaceous foraminifera merges insensibly into the more general topic of Pre-Carboniferous micropaleontology.

EARLY AND MIDDLE PALEOZOIC MICROPALEONTOLOGY.

Pre-Carboniferous micropaleontology was of small importance and had a scanty bibliography less than a score of years ago. The list of earlier Paleozoic microfossils, however, has recently been growing with amazing rapidity, and we now know that they can

[10] Eisenack, A., New Microfossilien des baltischen Silurs. I, II and III. Paleont. Ztschr., 13, 1931; 14, 1932; 16, 1934. ——, Neue Microfossilien des bohemischen Silurs. Paleont. Ztschr., 16, 1934.

be employed successfully to correlate the older strata. Because many of these beds have been considered essentially non-fossiliferous, and because oil is being produced in increasing quantities from some of these older strata, the search for microscopic indices in these rocks has a commercial as well as an academic urge. The ostracodes are of great importance, though at present little used commercially, in this pre-Carboniferous correlation problem. Calcareous foraminifera as well as the arenaceous types have also been found, here, and especially in Europe, and doubtless in the future will be discovered in still greater abundance.

Radiolaria. I have elsewhere commented on the economic potentialities as well as the strange lack of interest in the Radiolaria. These beautiful fossils, which are known at least from the early Paleozoic to the Recent, may become of especial importance in the pre-Carboniferous rocks because of their occurrence in cherts and novaculites, on whose disputed origin their study should throw some light.

Scolecodonts and Conodonts. Scolecodonts and conodonts also are assuming increasing significance in the older formations and a gratifying amount of work is continuing to be produced on these groups whose importance is consistently underestimated. In addition, sponge spicules which, like the radiolaria and scolecodonts, are by no means limited to the Paleozoic are turning up in increasing abundance and diversification in the older strata, and they may eventually have some slight stratigraphic importance.

Bryozoa. But, in relation to their potential economic importance for general stratigraphic diagnoses, perhaps the most neglected of all groups is the phylum Bryozoa. Their detailed study in thin sections prepared from outcrop as well as subsurface samples promises to open a fertile frontier for many explorers if they can but conquer their fear of the unknown and the difficult.

ECHINODERM FRAGMENTS.

Another investigational topic that promises to have much economic value is research on echinoderm remains. Moore [11] has re-

[11] Moore, R. C., The use of fragmentary Crinoidal remains in stratigraphic paleontology. Denison Univ. Bull., Jour. Sci. Labs., 33: 165–250, 1938.

cently put the study of the ubiquitous crinoid fragments on a much more sound scientific basis, and in the hand of the expert these remains might well assume great utilitarian significance in some difficult oil field correlation problems. Similarly our studies [12] of holothurian remains demonstrate that such fragments have some, though perhaps rather limited, stratigraphic value.

In this connection, however, Mortensen,[13] the leading European student of the echinoderms, is convinced that isolated echinoderm plates are of doubtful value in stratigraphic diagnosis. In this regard he lists the ophiuroid remains as worst, the crinoid ossicles as in the main not much better, and the pedicellariae and holothurian spicules as the most diagnostic. We should be inclined to agree in general, although such detailed studies of crinoid and ophiuroid parts as carried on by Berry, Moore, and Weller indicate that even groups which *a priori* look hopeless will show some stratigraphic value in the hands of an expert.

MICROSCOPIC OR SEMI-MICROSCOPIC PLANTS.

Because both the paucity of time and the plenitude of audience ennui plead against the continuation to logical completion of such a review as we have begun, we will now discuss briefly only one other major group of micropaleontologic remains, viz., fossils of microscopic or semi-microscopic plants. Such groups as Charophytes, Diatoms, the so-called Flagellates, and Spores and Pollen in the main have been very much neglected, yet they all have at least potential importance in both academic and commercial fields.

Diatoms. Fossil diatoms are similar to other organisms in that they record a progressive evolutionary development. It follows therefore that they also should be used in the detailed correlation of some strata.

The oldest rocks in which undoubted diatoms have been found are of Cretaceous age, although possible representatives of the

[12] Croneis, Carey, and MacCormack, John, Fossil Holothuroidea. Jour. Paleo., 6: 111–148, 1932.

[13] Mortensen, Th., Stratigraphic applicability of the microscopic remains of Echino derms. Sencken., 20: 342–345, 1938.

group have been reported from strata as old as the Russian Triassic. It is probably safe to assume, therefore, that diatoms secreting skeletons of the type that characterize them now, have been thriving in marine waters at least as far back as the mid-Mesozoic. The invasion of fresh water habitats by the diatoms took place probably as early as the Oligocene and later fresh water beds contain species in an increasing variety. According to G. D. Hanna, the most active American student of *fossil* diatoms (on whom I have drawn heavily for this brief summary) the first appearance of a particular species may well permit the construction of a valuable time scale, because common forms achieved widespread geographic distribution rapidly. Study of the nature of the diatoms of former lake basins may well make possible the reconstruction of the meteorology, climatology, and physical geography especially of some of the Tertiary geological episodes.

Because the deposition of diatoms commonly appears to be seasonal and because the beds are thinly laminated, Hanna has suggested that detailed study of the laminations may provide an accurate estimate for the duration of various geological time divisions, especially the Miocene. Inasmuch as many diatoms are pelagic in habit, like some graptolites they were in the past (as today) subject in their movements to the vicissitudes of ocean currents. Thus widely separated deposits of the same age may contain essentially the same assemblage of species. This is a feature that should make the diatoms useful in intercontinental correlation, yet strangely enough, unlike the graptolites, they have been little used for this purpose.

Another peculiarity of the diatoms is that species multiplied to an almost fabulous extent during certain periods. The zones resulting from this proliferation have become at least partially known around the globe. On the other hand, there were times when only a very few species dominated marine waters, though their tests accumulated to form vast deposits. One would think that such a combination of features would make the diatoms ideal fossils for the solution of numerous stratigraphic problems in petroleum geology. Unfortunately, it is chiefly in fine-grained shales that

there is found good preservation of diatoms, and actually, according to Hanna, the conditions most favorable for fossilization are those under which there is deposition of acidic minerals such as rhyolitic ash. Thus, although the great beauty of the skeletons of the diatoms has long charmed the microscopists, the micropaleontologists dealing with diatoms as stratigraphic markers are about as rare as these extraordinary fossils are abundant, and they have as yet been little employed in the search for oil.

Hanna and Grant for some time have been carrying on experiments for a method of mounting diatoms in media of high index of refraction by evaporation in a vacuum.[14] By this method the diatoms can be mounted in a film as thin as half a wave length of light. Realgar, when this thin, is perfectly transparent and it has all of the advantages usually associated with mounting media with index of refraction of 2.4. The resolution of fine detail is said to be the best that has ever been attained with visual light. Hanna states that the method is not cumbersome and that it can be used for routine work in quantity.

It seems obvious that what is needed in the case of the diatoms is largely more able workers in a fertile field which has, peculiarly enough, seemed unattractive to most students.

Charophytes. Charophytes have come into some prominence in this country recently largely through the work of Peck,[15] whose researches seem to indicate for them a fair degree of stratigraphic utility. Harris, the leading English worker, however, seems to think that their importance as stratigraphic markers has been overestimated. Harris[16] has recently stated:

> The Charophytes are potentially of great stratigraphic value, since they occur in lake deposits in which zone fossils apart from shells of cyprids are often scanty. The organ found fossilized is normally the gyrogonite; this is a strong and neatly constructed body which at first sight

[14] Hanna, G. D., and Grant, W. M., Preliminary note on a technique for mounting diatoms in realgar and other substances. Journ. Roy. Micr. Soc., 59: 174–176, 1939.

[15] Peck, Raymond E., Morrison Charophyta from Wyoming. Jour. Paleo., 2: 83–90, 1937.

[16] Harris, T. M., British Purbeck Charophyta. British Museum of Natural History, 1939.

seems ideal for this purpose. Careful consideration of the available evidence has, however, led me to the conclusion that their value is likely to be rather small because the difficulties of recognizing the species are great.

Although their gyrogonites have been much studied, and a large number of species has been described, Harris only recently completed the first study of their range of variation. From his results he was forced to conclude that the range in the family is not "great enough to allow a very large number of specific groups to be distinguished with any certainty." Thus Harris woefully states in the form of a foreword to his monograph on the British Purbeck species:

> All that could fairly be claimed for the study of these fossil Charophytes would be that they had led to the clearing up of many of the problems that they themselves had raised.

I believe that this is entirely too pessimistic an attitude, but it must be remembered that the usefulness in petroleum geology of most charophytes, like that of some diatoms, may be somewhat reduced because of their fresh water sites of deposition.

Flagellates. The Flagellates comprise a richly varied group of lowly plants, of somewhat uncertain classificatory position in the organic world, which are almost unknown in this country, at least from the paleontologic point of view. They have attracted the attention of a number of European workers, however, and Deflandre[17] has ably summarized the knowledge concerning both modern and fossil representatives in a monograph that should be in every subsurface laboratory, but which is virtually unknown in this country. The Silicoflagellates, Coccoliths, and Dinoflagellates, which are discussed very briefly here, comprise only a few of the groups considered by Deflandre.

Silicoflagellates are widespread, entirely marine, planktonic flagellates with a siliceous skeleton. They occur in all latitudes and the cold and warm water assemblages show some significant differences. Known from the Cretaceous (Senonian) to the present, the Silicoflagellates have been studied thus far chiefly if

[17] Deflandre, Georges, Les Flagelles Fossiles. Paris, 1936.

not entirely in diatomites, whose origin they at least partially certify to be planktonic. Certain deposits are so rich in the fossil remains that Deflandre is justified in calling them "Silicoflagellites," yet the American economic paleontologists interested in this group can be counted on the fingers of one hand, and Hanna [18] is the only active worker in the field.

Coccoliths are Flagellates whose cells have a calcareous covering. They make up part of the nannoplankton of present seas, and also are known to live in brackish and in fresh water. Coccoliths belong to various groups, chief among which are the plain *discoliths,* and the *tremaliths,* which have an axial perforation. Tremaliths with a short tube are called *placoliths;* those with a long tube *rhabdoliths.* The latter are especially characteristic and easy to distinguish, and some authors recognize only these, putting all other forms under the general heading *coccoliths.* There are many other rarer forms, and some exhibit polymorphism so that a single species may be represented by two types of coccoliths.

A century ago Ehrenberg discovered these calcareous bodies in the chalk, and for a long time he considered them inorganic. Huxley (1857) found recent coccoliths in materials dredged in the north Atlantic and at about the same time Wallich reported coccoliths forming spherules, which he called *coccospheres.* Sorby (1861) found coccoliths and coccospheres well preserved in the chalk of England. Lohmann [19] in a series of papers (1902–1912) advanced the study of the biology, classification and ecology of these forms. Gran and Ostenfeld described new species, Kampner (1927–1928) made important contributions, and Schiller's [20] studies (1913–1935) brought the subject of coccoliths to its present status.

[18] Hanna, G. D., Silicoflagellata from the Cretaceous of California. Jour. Paleo., 1: 259–263, 1928. ——, New genus of Silicoflagellata from the Miocene of Lower California. Jour. Paleo., 4: 415–416, 1930. ——, Diatoms and Silicoflagellates from the Kreyenhagen shale. Mining in California, 27: 187–201, 1931.

[19] Lohmann, H., Die Coccolithophoridae. Arch. f. Protistenk, Vol. 1, 1902. ——, Untersuchungen ueber das Pflanzen- und Tierbelen der Hochsee, Veroff. d. Inst. f. Meersk. Neue F. A. Geog.-naturw. Reihe. Heft I, 1912.

[20] Schiller, J., Die planktontischen Vegetationen des adriatischen Meeres. Arch. f. Protistenk. LIII, 1925. ——, In Rabenhorst's Kryptogamenflora, 10: 1935, which see for other references.

The Challenger expedition found enormous quantities of coccoliths in most oozes of warm seas, and globigerina ooze also contains a high proportion of them. In addition Kamptner and Schiller have found them important in the Adriatic and the Mediterranean. They are equally significant in rock formation. C. W. Gümbel (1870–73) was the only investigator of the 19th century to study them carefully in marine deposits. He reported them from Jurassic, Triassic, and even Cambrian strata, whereas Louis Dangeard[21] (1932) has described them from the Oligocene beds of Limagne. But it is a rare geologist who has even noted the presence of coccoliths or rhabdoliths and there is no American worker. A few men such as Dangeard and Tan Sin Hok (1931), however, have determined species, Hok having found a number of modern forms in a Tertiary (Pliocene?) marl on the isle of Rotti in the Moluccas.

Practically nothing is known of speciation before the Cretaceous, but disciform, simple coccoliths do occur in the older beds, and the more complex forms had appeared before the end of the Cretaceous. L. Cayeux[22] has maintained that it has been almost impossible to identify fossil coccoliths and rhabdoliths in well consolidated deposits, but he has also suggested that further study of them should be carried on with such sediments as those of the Carboniferous of Russia.

Discoasterids[23] are minute stars or disks resembling coccoliths to which forms they are probably related. Ehrenberg, who first reported them, thought of them as calcareous concretions. Finding them in many marls and chalks, he at one time admitted their organic nature, but later he rejected his admission. Sorby (1861), who found them in the chalk of England, and Hill (1895), who listed them from the Barbados, thought they repre-

[21] Dangeard, Louis, Les Craies a Coccolithes de la Limagne. Bull. Soc. Geol. Fr. 5th Ser., 2: 1932.

[22] Cayeux, L., Les roches sedimentaires de France. Roches carbonatees. Paris, Masson, p. 84, 1935.

[23] Tan, Sin Hok, Discoasteridae incertae sedis. Proc. K. Akad. Wet. Amsterdam, 30: pt. 3, 1927. ——, Discoasteridae, Coccolithinae and Radiolaria. Leidsche. Geol. Mededeel. Leiden., 4: 1931. Deflandre, G., Les Discoasterides. Bull. Soc. franc. de Microsc., 3: 1934.

sented calcareous crystals. Jukes-Brown and Harrison (1892) described them in rocks of the west coast of Java and Haupt (1906) investigated a chalky marl of New Guinea in which Discoasterids were rock formers. Moreover, Tan Sin Hok has calculated that in strata (probably Pliocene) from one of the Sunda Isles there are 55×10^{14} discoasters per cubic meter! Why no American economic paleontologist has become interested in these fossils is hard to explain.

Dinoflagellates [24] secrete a cellulosic capsule and are found in all oceans and in many fresh water bodies. Ehrenberg [25] discovered their remains in flint and mentioned them in his pioneering work of 1854, "Mikrogeologie." W. Wetzel [26] (1922) confirmed Ehrenberg's observations and O. Wetzel [27] later (1933) published important studies of their remains. Deflandre (1933–35), Lefevre (1932–33), and Eisenack [28] (1935) also have prepared significant papers on this group. O. Wetzel (1935) has shown that Peridiniens occur in a clay of the upper Eocene from northern Germany, and that their organic matter has been preserved just as in some flints. Eisenack also described a new genus of *siliceous Peridiniens,* which he found in Jurassic calcareous sandstone. These are indisputable Dinoflagellates, and the most ancient yet known. Their method of fossilization is difficult to explain at present, for the fossils represent an unusual case of *silicification* of apparently cellulosic material in the midst of rocks themselves made up of perfectly preserved siliceous microfossils such as sponge spicules, Diatoms, Radiolaria, and Silicoflagellates. Possibly the organisms originally secreted siliceous capsules for the circumstances under which the Jurassic

[24] See Schiller, reference 20, for bibliography.

[25] Ehrenberg, C. G., Mikrogeologie. Leipzig, 1854.

[26] Wetzel, W., Sedimentpetrographische Studien. I. Feuerstein. N. Jhb. f. Min. Beil., 47: 1922.

[27] Wetzel, O., Die in organischen Substanz erhaltenen Mikrofossilien des Baltischen Kreide Feuersteins. Palaeontographica, 67–68: 1933. ——, Mikropaleontology des Heiligenhafener Kieseltones (Ober-Eozän). Niedersächs. geol. Ver. Hannover, Jahresber, 27: 1935.

[28] Eisenack, A., Mikrofossilien aus Doggerdeschieben Ostpreussens. Ztschr. f. Goschiebeforschung, 11: 1935.

siliceous Peridiniens of Eisenack occur present a new argument in favor of the hypothesis that in some of the Dinoflagellates the sheath was secreted of siliceous material.

Spores and Pollen. Although studies of Spores and Pollen properly belong in this same general category, some of paleobotanical aspects of this promising phase of economic micropaleontology recently have received gratifying attention from American workers, and have been discussed at these symposia. I shall, therefore, omit further consideration of them here.

Algal Dust. Before concluding this phase of the discussion, Wood's [29] concept of algal dust should be given brief consideration. The English geologist states:

> 'Algal dust'. . . is an associate of algal action in the Carboniferous Limestone. There is a complete transition from algal nodules with strongly marked tubes (*Mitcheldeania gregaria* Nich.) through forms with looser tubes (*Ortonella furcata* Garw.) to those consisting of vague aggregations of tubes (some species of *Bevocastria*). The final stage is that of the *Spongiostroma* precipitates with no definite organic structure preserved. The different appearances depend on the type of alga making up the nodule, and on the rapidity of decay of the organic matter, but the association of algal dust with algal traces appears to be constant.

Wood concludes that "algal dust" contributed to the formation of many Carboniferous (and probably other) limestones, and that some peculiar lithologic types can in part be explained on the basis of this contribution. The few American workers (such as J. Harlan Johnson) on fossil algae should receive reinforcements in the form of students who would be well rewarded for entering a field with sedimentological and paleontological promise, much of which may have an economic import.

SEDIMENTOLOGICAL AND ECOLOGICAL RELATIONSHIPS.

Turning briefly to another topic, it may be reiterated that however many new micropaleontologic groups are discovered, their full academic and economic possibilities will never be realized until they are studied in their proper and complete ecological re-

[29] Wood, Alan, Algal Dust. Geol. Mag., 78: 192–199, 1941.

lationships. Especially is this true since the location of stratigraphic rather than structural traps for petroleum has become increasingly important. Therefore the micropaleontologist must now be trained, as I have advocated elsewhere, in sedimentology, micromineralogy, and biology. It is no more possible to analyze completely a sediment on the basis of its foraminiferal content alone, however varied, than it is to understand wholly a complex tamarack swamp assemblage on the basis of elaborate studies of the *tamaracks alone.*

Professor Krumbein will very shortly demonstrate that heavy mineral analysis may or may not be effective in correlation, and that it is far from impossible for entirely different environments locally to produce the same kind of sediment, or for a single environment to produce different sediments in different places. The same sort of statement applies with equal cogency to the micropaleontological province as well as to the micromineralogical. In order to solve even partially some of the problems which grow out of these seeming paradoxes, it is becoming necessary for the micropaleontologist who wishes to be on the frontier of his field also to study paleoecology. Professor T. W. Vaughan [30] pointed out in his presidential address before the Geological Society of America in 1939 that there are at least two different approaches to the subject of paleoecology. First, there is the investigation of all the environmental relationships of the organic and sedimentary assemblage *as a unit.* Such an investigation must be carried on for each of the environmental types represented in the strata to be studied. Second, there may be an investigation of the ecology of *specific* organic and sedimentary components throughout their geological and geographical ranges in one or more assemblages or environmental categories. No petroleum corporation has yet urged, and few have even permitted, their economic paleontologists to follow either of these lines of investigation to their fullest extent largely because their economic bearing, although potentially great, is not obvious. S. W. Lowman's recent work on the eco-

[30] Vaughan, T. W., Ecology of modern marine organisms with reference to paleogeography. Bull. G. S. A., 51: 437, 1940.

logical relationships of brackish- and shallow-water foraminifera from Louisiana, however, indicates that the economic aspects of such investigations are at least becoming apparent in some administrative quarters.

The paleontological components of a sediment may have suffered, since the time of their incorporation, at least as many vicissitudes as the sediments themselves. The role of diagenetic changes, however, in the modification of micropaleontologic assemblages is commonly overlooked or minimized. Yet it is well known to most students of the subject that many fine-grained marine sediments make many journeys through intestinal tracts before they are indurated. During these passages there are some erosional effects, organic matter is eliminated or altered, chemical changes take place and the organic remains themselves are likely to be destroyed or altered. Twenhofel [31] has demonstrated that some of these phenomena are operative for fresh water as well as marine sediments, and he has shown that microorganisms are responsible for the progressive downward diminution of the organic material in some lake sediments. Be it noted also in this connection that the organisms responsible for this marked sedimentological change are almost certain not to be incorporated into the micropaleontologic record. Thus it is seen that the fossil assemblage is not only partially dependent upon diagenetic history, but that the original organic assemblage, commonly a far different thing, may have been in part responsible for major events in that history.

It also follows that the organic components of a sediment that somehow persist in the surficial or transportational realms are almost as likely to be removed, or altered beyond recognition, even after being buried, as they are to be preserved by some one of the various fossilization processes. For all of these and other reasons there may well be major similarities in the micropaleontologic aspect of various non-contemporary faunas. Equally awkward is the fact that known contemporaneous and similar faunas may become relatively unlike in micropaleontologic aspect. This results

[31] Twenhofel, W. H., Physical and chemical characteristics of the sediments of Late Mendota. Jour. Sed. Pet., 3: 68–76, 1933.

from unusually favorable conditions for the preservation of certain elements of the original fauna in the one sediment, and the lack of incorporation of, or the destruction of, other elements of the original assemblage in the second sediment.[32]

Important as they are it is not my purpose to explore these paleoecological problems further in this paper, but the unavoidable difficulties introduced into accurate economic micropaleontologic work by the differences between the *biocoenotic* (or life), assemblage, which we should like to reconstruct, and the *thanatocoenotic* (or death) association,[33] with which we deal, must be taken into careful consideration for their lack of recognition by the economic paleontologist may even result in large financial losses or missed opportunities for his company and the nation.

CONCLUSION.

I have attempted to point out the many animal and plant groups that are potentially of consequence in any imaginative search for oil, but which today are scarcely considered by American workers. I have also tried to show something of the complexity of the micropaleontologic frontiers. Perhaps the very fact that it is no longer a simple geological problem to find new micropaleontological techniques or new oil resources is a good omen for the economic paleontologist.

Most beginning students in petroleum geology are disillusioned when first they discover that the sweetly reasonable anticlinal theory is no longer of pristine importance now that surface methods have long since pretty well outlined most of the obvious structural traps. In fact, were only anticlines to be drilled today, most geologists would find themselves unemployed. As the problem of discovering petroleum traps becomes even more complicated, sedimentological studies involving micromineralogic and micropaleon-

[32] This entire topic has been extensively considered in a doctorial thesis prepared at this Department by Thomas G. Payne entitled "Stratigraphical Analysis and Environmental Reconstruction" which is soon to be published.

[33] Wasmund, Erich, Biocoenose und Thanatocoenose. Arch. f. Hydrobiologie, 17: 1–116, 1926. This masterful paper is unfortunately essentially unknown to geologists in this country.

tologic pursuits once thought of as only "academic" become intensely practical, and the geologist's position in the industry, as well as in defense effort, is certain to become more, rather than less, secure. Thus, despite the fact that we characteristically must disabuse ourselves of the notion that nature is simple, her very complexities are actually the reason for being of the petroleum geologist in all of his varieties, even including the micropaleontological.

May I terminate these remarks with brief mention of another topic in economic versus academic geology, which transcends micropaleontology, or any other ology, in importance.

Levorsen has pointed out the case of the, fortunately unidentified, geology professor whose teaching is ten years behind the time; and we have all heard that absurd archeozoic chromo regarding the lucky third generation Harvard student who did not have to attend classes because he had inherited his grandfather's notes. Regrettably enough, a few of these stories may have been founded on fact. Today, however, such tales are *chiefly* apocryphal. If they are not *entirely* apocryphal it is because not only the entire geological curriculum, but all the minutiæ of course context, are changing so rapidly that few students, or instructors, for that matter, can keep pace with the metamorphosis. But we academicians, at least in some cases, *are* guilty of a presumptuous acàdemic attitude that is serious if only because unconsciously it may be transmitted to students, who, upon entering the petroleum, or any other economic, field, assume that they understand all the ramifying phases of the work merely because they have had graduate training. It is also an especially unwarranted pose because actually some of us *have* failed to keep pace with our rapidly moving fellow scientists in the business world. Because our subject's farthest frontiers are only to be reached through the skillful cooperation of both academic and commercial geologists, it is particularly important that we lower rather than elevate any barriers which may yet exist between us. Happily ever since the Tulsa meeting of the Geological Society of America the scholasticists have had their eyes at least partially opened to the fact that

some advances in petroleum geology are of fundamental scientific importance, and that not only the curricula in geology must be improved constantly to keep up with the needs of the oil geologists, but the academic men themselves must increase *their* exploration activities or they will find that their cousins in the economic world are the only true frontiersmen in the science. On the other hand the economic geologists must become more willing to acknowledge (and to aid in the development of) ideas originating in cloistered halls far from the economic "firing line." Fortunately the more or less natural reciprocally critical attitude of many academic and economic geologists has, we dare to believe, less foundation at the present time than ever in the past, and we may look forward to the time when mutual suspicion will give way completely to mutual understanding and cooperation.

UNIVERSITY OF CHICAGO,
CHICAGO, ILL.,
December 22, 1941.

STRUCTURES IN THE THOMSON FORMATION, MINNESOTA.[1]

GEORGE M. SCHWARTZ.

ABSTRACT.

The series of slates and graywackes exposed over a large area southwest of Duluth show much deformation. As a result diagrammatic structures are common and show the relation between structures unusually well. The use and limitations of minor structures in determining the major structure of a region are demonstrated.

The significance of structure in the correlation of the formation is unusually important. As a result of structural studies supported by other data, it is concluded that the formation is not Animikie but is older than the unconformity at the base of the Animikie, that is the formation is pre-Algoman.

INTRODUCTION.

THE slates along the St. Louis River in northeastern Minnesota have long been known to furnish diagrammatic examples of the relations of various structures found in a series of deformed and metamorphosed sediments. Until recently little detailed mapping of these slates had been done. During the field seasons of 1939 and 1940 the entire area of known outcrops was mapped on a scale of six inches to the mile, or on a still larger scale where the detail required more map space.

This work is part of a Minnesota Geological Survey project to restudy the area in and around Duluth and work out the regional geology in detail. Structural details obtained on this work furnish excellent examples of the varied structures that may be expected in such a deformed and metamorphosed area. The uses and limitations of each type of structure in working out the regional structure are suggested. The structures, particularly the folding, have an important bearing on the correlation and sig-

[1] Published with the permission of the Director of the Minnesota Geological Survey.

nificance of the Thomson formation, which in turn furnishes a clue to the geology of a large covered area in northeastern Minnesota south of the Mesabi range.

LOCATION OF THE AREA.

The Thomson slate was named by N. H. Winchell [2] for the extensive exposures in the village of Thomson on the east side of the St. Louis River in Carlton County, Minnesota. The slates have also been referred to as the St. Louis slates, Cloquet slates and Carlton slates. The name Thomson has priority, as noted by Miss Wilmarth.[3] Because graywacke and graywacke-slate are more abundant than slate, the name should be Thomson formation rather than Thomson slate.

The exposures of the Thomson formation occur mainly in Carlton County from Cloquet southeastward along the St. Louis River to the outskirts of Duluth and southwestward along the abandoned outlets of the glacial stages of Lake Superior. Some outcrops occur adjacent to Carlton County in the northwest corner of Pine County, along the headwaters of the Kettle River. A few exposures also occur in St. Louis County west of Duluth and at Little Falls on the Mississippi River.

The main area of outcrops described above extends about 40 miles east and west and 25 miles north and south, with most of the exposures along the southwest northeast diagonal of the area. Drill records and other data indicate that the formation extends widely to the north and west under a heavy cover of glacial drift.

STRATIGRAPHIC RELATIONS.

The stratigraphic position of the Thomson formation has been a matter of debate and it has been variously correlated, but with little direct evidence in favor of any correlation. Intensive studies

[2] Spurr, J. E.: The stratigraphic position of the Thomson slates. Am. Jour. Sci., 3rd ser., 48: 159–166, 1894.

[3] Lexicon of geologic names of the United States. U. S. Geol. Surv. Bull. 896, p. 2141, 1938.

of the entire area of its occurrence, and of adjacent areas as well, give little or no evidence that the formation is Upper Huronian (Animikie) as it has often been classified in recent years, but suggest that the formation is to be correlated with the slates of the Lower Huronian, or even older beds, comparable with the Knife Lake slates of the Vermilion iron district in Minnesota. Perhaps the strongest evidence of the pre-Animikie age is furnished by the structures described below.

Spurr [4] and N. H. Winchell [5] in early writings, correlated the slates and associated beds with the Lower Huronian (Keewatin of Minnesota at that date). Later Winchell believed the slates at Carlton to be Animikie as he had thought previous to Spurr's work. Van Hise and Leith,[6] and later Leith, Lund and Leith,[7] have correlated the slates in Carlton County with the Virginia slates.

A detailed presentation of the evidence bearing on the correlation of the Thomson formation will be given in a paper now in preparation. It is sufficient for present purposes to say that it is rather definitely pre-Algoman in age.

The Thomson formation consists of an interbedded series of slates, graywacke slates, and graywackes. The graywackes, because of their resistance to erosion, form conspicuous outcrops (Fig. 1). There evidently was a repetition of these three types of sediments over and over again without any characteristic horizon markers. Conditions of sedimentation must have remained such that these mixtures of clastic sediments with some carbonate were deposited continuously over a long period of time without any great disturbance.

[4] The stratigraphic position of the Thomson slates. Am. Jour. Sci., 3rd ser., 48: 159–166, 1894.

[5] Geology of Minnesota. Minnesota Geol. and Nat. Hist. Surv. Final Rept., 4: 531–553, 1899.

[6] The geology of the Lake Superior region. U. S. Geol. Surv. Mon. 52, p. 212, 1911.

[7] Pre-Cambrian rocks of the Lake Superior region. U. S. Geol. Surv. Prof. Paper. 184, 1935.

REGIONAL STRUCTURE.

The Thomson formation, occupying an area west and southwest of the head of Lake Superior and southwest of Duluth, is on the north limb of the Lake Superior geosyncline. It should be noted on the geologic map (Plate 1) accompanying United States Geological Survey Monograph 52, that the main axis of the Lake Superior geosyncline does not pass through the head of the Lake

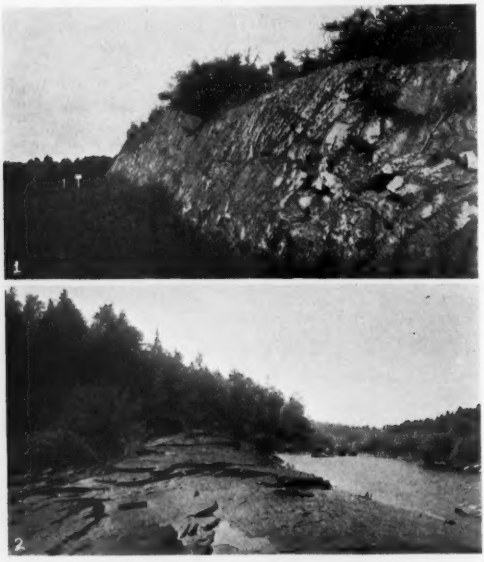

FIG. 1. Bedding plane cliff of graywacke; the opposite side is a joint plane. Northern Pacific Railway, just east of St. Louis River.

FIG. 2. Flat anticline pitching gently eastward forming an uncommon anticlinal ridge. St. Louis River.

(Duluth-Superior) but strikes the south shore near Ashland, Wisconsin, and thence trends southwesterly across Wisconsin into Minnesota. This general location of the axis and the evidence

for it was emphasized by Thwaites [8] in the results of his work on the south shore of Lake Superior.

A minor axis of the geosynclinal folding passes south of Duluth and Superior, but the nearest outcrops of Thomson formation are fully 10 miles to the northwest of even this minor axis. The complex folding of the Thomson formation is clearly not a result of the deformation that resulted in the Lake Superior geosyncline, but is rather the result of one of the older periods of folding that affected the rocks of the Lake Superior region and the pre-Cambrian shield in general. The lower and middle Keweenawan rocks involved in the geosynclinal folding lie unconformably at gentle angles on the complexly folded Thomson slate. An exposure in the bed of the St. Louis River, which has not been previously described, shows the unconformity with a quartz pebble conglomerate lying on slate. The conglomerate strikes N 60° E and dips 7° SE, whereas the slate strikes N 70° E and dips 45° S. The slaty cleavage strikes N 88° E and dips 50° N.

About six miles northeast of the conglomerate just described and two miles west of the Duluth city limits is a good series of exposures in sections 17 and 20 of T 49 N., R 15 W. One-fourth mile east of the northwest corner of section 20, Thomson beds, Puckwunge conglomerate and sandstone, and Middle Keweenawan lava flows are all exposed within a distance of 350 feet of each other. The Thomson beds strike N 85° E and dip 84° S, whereas the Puckwunge beds above strike N 10° W and dip 15° E. The pronounced structural discordance of the two formations is evident wherever they are exposed near each other. The overlying flow has an attitude similar to that of the Puckwunge and this fits into the regional Lake Superior structure (Sandberg, 1938, p 797), but the Thomson beds clearly owe their structure to an earlier deformation.

There is abundant evidence of a gentle deformation later than the main period of development of the slaty cleavage of Thomson

[8] Sandstones of the Wisconsin coast of Lake Superior. Wis. Geol. and Nat. Hist. Surv. Bull. 25, p. 88, 1912.

formation. It is entirely possible that this later gentle deformation is related to the deformation of the Lake Superior geosyncline. The seven to fifteen degree dips of the basal Keweenawan conglomerate represents about the prevalent angle of dip of Keweenawan and Animikie rocks for the Minnesota coast of Lake Superior from Duluth to Pigeon Point.[9] The deformation and slaty cleavage found in the Thomson formation below the unconformity clearly preceded the formation of the Superior geosyncline as it now exists, and represent about the same degree of deformation and metamorphism as the Knife Lake slates of the Vermilion district.[10]

DETAILED STRUCTURE.

Folds.

General Description.—The exposures of the Thomson formation show abundant evidence of folding but complete folds are revealed only locally and these are mainly minor folds, at least of the second order. When detailed mapping was started it was expected that the regional structure of the area could be worked out by the application of the principles of the relation of minor to major structures. This expectation was only partially realized. Deterring factors are: lack of outcrops in critical areas, and even more serious, the lack of recognizable horizons in the formation. Minor structures give a fairly accurate picture of the kind of folding and of the general location of major and minor axes, but without key beds to trace the outline and determine repetitions, any regional structure that may be inferred is bound to be but one of several possibilities.

The prevalent strike of the beds in exposures throughout the main area of outcrop of the Thomson beds is nearly east-west. The same is true of the cleavage; its strike generally varies only slightly from that of the beds, but its dip is generally much steeper. The prevalent east-west strike of slaty cleavage and bedding

[9] See for example details presented in Minnesota Geol. Surv. Bulls. 24 and 28.

[10] Gruner, J. W.: Structural geology of the Knife Lake area of northeastern Minnesota. G. S. A. Bull., 52: 1577–1642, 1941.

shows that the major folds strike east-west in contrast to the northeast-southwest strike of the Animikie and Keweenawan beds and fold axes of northeastern Minnesota.[11]

Where the strike of the beds and cleavage is nearly parallel erosion has resulted in many long narrow ridges (Fig. 1). These are conspicuous on aerial photographs and furnish a good check on the prevalence of east-west strikes of the beds. Where the strike of the cleavage is at an angle to the beds of slate, ridges do not continue far, as erosion along the cleavage seems to have destroyed their continuity. The general elongate shape and rounded profile of the ridges suggest the possibility of their being folds, but actually this is rarely the case. They are mostly rounded resistant beds.

The dip of the beds is generally moderate. The average of 225 south dips is 53° and of 80 north dips 57°. The moderate dip and the slight difference between the north and south dips indicate that the major folds are of an open type and nearly symmetrical. This is also indicated by rather low open minor folds (Fig. 2). Tabulation of 544 well-distributed dip observations, with general east-west strikes over the area of outcrop shows that 71 per cent are to the south. Averages along strips both north and south and east and west gave about the same percentages as those given for the entire area. At places, as along the St. Louis River, exposures are continuous enough to eliminate the danger of missing north dips. Dips to the east or to the west are comparatively few. The results of this tabulation agree with the field impressions. This prevalence of south dips was noted long ago by N. H. Winchell.[12] It seems, therefore, that the considerable width of outcrops across the strike indicates a great thickness of beds rather than simply repetition of the beds by folding although this certainly prevails to some extent. A graphic solution of the problem shows that forty-two per cent (i.e. 79–29) of the outcrop width may be used to estimate possible thickness of the formation. An estimate of 45,000 feet of beds results for a north-

11 See, for example, Plate 1, U. S. Geol. Surv. Prof. Pap. 184.

12 *Op. cit.*

south extent of outcrops of 25 miles. If a 50 per cent reduction is made to allow for the flat dips on the axes of anticlines and synclines and undiscovered causes of duplication, the thickness of the formation is still imposing.

The pitch of folds in the Thomson beds is shown especially well by the trace of the bedding on weathered surfaces of the slaty cleavage. The pitch of the bedding shows up plainly (Fig. 7), is easily read, and the consistency of the readings suggests that the observations are particularly dependable. The pitch of drag folds coincides with the general pitch of major folds and was used where the trace of the bedding was not visible. The fact that most major folds pitch gently eastward, is brought out graphically by the plotting of pitch observations (Fig. 3). This shows that the

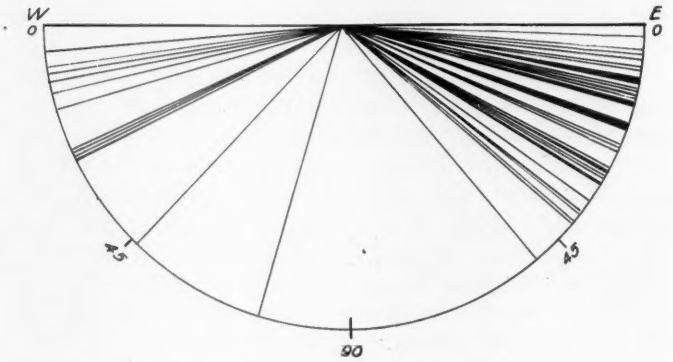

FIG. 3. Diagram showing angles of pitch of minor folds and trace of bedding on cleavage plane. 54 observations.

majority of folds pitch east between 10 and 30 degrees. The eastward pitch was no doubt increased about 10 degrees by the late Keweenawan sinking of the Superior geosyncline. The pitch previous to that may be approximated by rotating the semicircle of Fig. 3, 10 degrees counterclockwise. About six of the east pitches would then pitch west and five would be horizontal. The great predominance of east pitches would thus largely disappear.

The effect of later deformation on a series of folds might easily be overlooked in examples of this sort.

Inasmuch as the strike of the beds is normally about east-west, the axial planes are oriented in that direction; nearly symmetrical minor folds and equal dips on the limbs indicate that the axial planes are nearly vertical and pitch east as shown above. The beds to the west are thus generally beneath those of the east. The gentle pitch of the folds results in many outcrops gradually plunging beneath the drift, in the direction of pitch. This is true, not only of anticlinal exposures but also of the resistant beds on the limbs of folds or in regions of monoclinal dips.

A summary of known facts and inferences regarding the folds of the area serves to clarify the situation:

Facts.

1. The strike of the beds is mainly east-west.
2. The dip of the beds is south and north in the ratio of 71 to 29. The dips average about 55 degrees.
3. The strike of the flow-cleavage is also generally east-west.
4. The dip of the cleavage is almost invariably steeper than that of the beds.
5. The pitch of the folds is low and mainly to the east, but west pitches also occur.
6. Minor folds are often broad and open, others are only mildly asymmetrical.

Inferences.

1. The axes of the major folds strike generally east-west.
2. The major folds are of a rather open, nearly symmetrical type and isoclinal and overturned folds are generally absent as shown by the fact that the cleavage always dips steeper than the bedding.
3. The axial planes of the major folds are nearly vertical.
4. The thickness of the beds represented by the outcrops is great because of the generally east-west strike of the beds and predominant south dips.

Dips and strikes of bedding and cleavage were plotted for the area of principal outcrop on a scale of four inches to the mile. Anticlinal and synclinal axes were then sketched in wherever suggested by the dip of the bedding. In general it was found that

minor axes with trends varying not over 15 degrees from east-west were fairly common, but it was as a rule impossible to extend these axes for any great distance. Few could be mapped over a length of a mile with any degree of confidence. Lack of outcrops often prevented extension, but in areas of abundant exposures projection of axes was prevented by observations indicating only monoclinal dips.

A few exceptions to the above general statements deserve mention. In the south half of sections 7 and 8 of T 48 N, R 16 W, a well defined syncline trends N 84° E for nearly two miles. Uniform southerly dips seem to preclude its extension eastward beyond the east line of Section 8. Lack of outcrops to the west leaves its extension westward an open question.

In the south half of sections 31 and 32, T 49 N, R 16 W an anticline extends across both sections near the south line. In section 32 the axis trends east-west. In section 31 the trend is S 83° E. The axis extends into section 36 of the adjacent township where it may swing sharply northwest and connect with an anticlinal axis southeast of the center of the section. To the north of this anticlinal axis from one-fourth to three-eighths of a mile is a nearly parallel synclinal axis of about the same length. Lack of outcrops at each end leaves open the possibility that this axis extends considerably farther.

A few folds were noted on aerial photographs available for the area along the St. Louis River, through the courtesy of the Minnesota Power and Light Company. North of the Thomson reservoir in the northeast portion of Sec 5, T 48 N, R 16 W, a distinct syncline is indicated on the photograph. Massive graywacke beds form dip slopes that show the curve of the bed. The pitch is to the east and older beds successively appear along the axis, from east to west. The pitch is 15 degrees east and the dip on the limbs varies from 15 to 78 degrees, but most are near 35 degrees. A small sharp anticlinal axis exists on the south side, but is only partially exposed.

Minor Folds.—Many minor folds were observed. These need not be described in detail but characteristic examples will be men-

tioned with illustrations. Small folds a few feet, or at most a few tens of feet, across were observed in the better exposures (Fig. 2). Some are broad open symmetrical folds in the more massive beds, for example beneath the bridge over the St. Louis River in Jay Cooke Park. In the slaty beds, the folds are more likely to be somewhat asymmetrical, doubtless a result of differential movement on the limb of a large fold. A good example occurs in a Great Northern railway cut about 1000 feet north of Highway 61, at the west edge of Carlton. Along the St. Louis River where exposures are particularly good very flat gently pitching open folds were observed (Fig. 2). In the reservoirs above the dams the anticlinal ridges form well defined reefs projecting out into the river. A good example may also be seen just below the Scanlon dam.

Much more minute folding, often measured in inches, is common, and presents considerable variety. Some of these gentle, wavy, small folds resemble ripple marks on the bedding planes, and only by examining the cross-sections of the rocks affected can they be distinguished. The criterion used is that in folding the rock must show the structure in successive layers in cross-section. Ripple marks show only the single apparent fold at the bedding plane. The minute folds naturally occur in the slaty beds that were relatively incompetent. An extreme example was noted in a Northern Pacific railway cut southeast of Carlton (NW ¼ SW ¼ Sec 8, T 48 N, R 6 W). Here the bedding plane has a fluted appearance as a result of folding with the distance from crest to crest only an inch or two (Fig. 4). In cross-section the folds are asymmetrical indicating the relative shear of the beds. Quartz veins commonly follow minor folds and emphasize them (Fig. 5). Some of the more complex vein quartz folds resemble ptygmatic folds as for example in Section 8, T 48 N, R 16 W, southeast of Carlton. Many other examples were noted. Some of the quartz folds are asymmetrical indicating differential movement in beds, but most are symmetrical or irregular.

Isoclinal folds are rare in the Thomson formation, but in the highly metamorphosed beds near the granite contact in north-

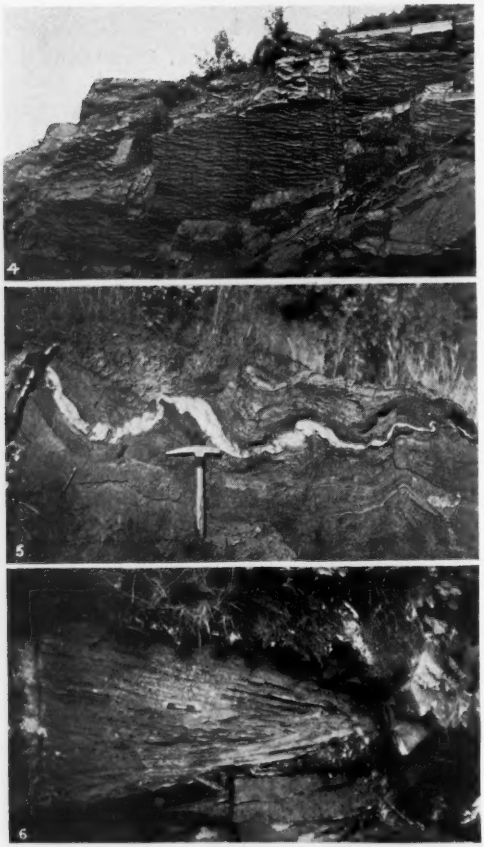

FIG. 4. Minute folding in slate which expresses itself as a fluting on bedding plane. Northern Pacific Railway, Sec 8, T 48 N, R 18 W.

FIG. 5. Vein quartz formed along minor folds in phyllite; just west of Atkinson, Carlton County.

FIG. 6. Recumbent drag fold. Valley of Gillespie Brook, Sec 22, T 46 N, R 20 W.

western Pine County, close folding is more common, for example on Gillespie Brook in Section 22, T 46 N, R 20 W a recumbent isoclinical fold (Fig. 6) occurs in a mica schist between more massive graywacke beds.

Slaty Cleavage.

General Statement.—The slate beds of the Thomson formation throughout its known exposures exhibit excellent slaty cleavage, varying to well-developed schistosity in the exposures 25 miles southwest of Carlton in Pine County near granite intrusives. This structure is particularly noteworthy when compared with the absence of cleavage in the Virginia slate with which the Thomson has often been correlated.

In the vicinity of Carlton and Cloquet where exposures are most extensive, the slaty cleavage is highly developed and affords diagrammatic relations between flow cleavage, bedding, fracture cleavage and minor folds. The highly argillaceous beds have excellent slaty cleavage. Argillaceous material mixed with sandy material has formed graywacke slates that show cleavage from well cleaved slates to almost massive beds with poorly developed cleavage. Massive graywacke beds with jointing and fracturing are abundant throughout most of the formation. Cleavage is lacking in many of these massive competent beds, but thin-sections show that sericite and other elongate or platy minerals are commonly oriented. In the more highly metamorphosed area near the granite, graywacke beds form a very quartzose mica-garnet-schist, and west of Denham gneiss occurs in certain zones.

Relation of Slaty Cleavage to Bedding.—A great variety of relations were observed between the slaty cleavage and the bedding. In general, however, the angle between the two is relatively large indicating, along with other evidence, that the major folds are of a relatively open type. The pitch is commonly indicated by the trace of the bedding on the cleavage planes (Fig. 7).

At places, the flow cleavage and bedding planes appear to coincide, or are so closely parallel that any divergence is not easily detected. In general, thin slate beds show an acute angle between bedding and cleavage.

As previously noted, the average dip of the beds in the main area of outcrop is about 55 degrees. The cleavage is always steeper than the bedding (Fig. 8) except where the two are parallel. Tabulation of 100 south-dipping cleavage planes gave an average dip of 73 degrees, whereas 48 north dips averaged 78. In addition, there were several vertical dips excluded from the

FIG. 7. Trace of bedding dipping about 40 degrees to the east (right) on cleavage plane indicating an eastward pitching fold. West of Northwest Paper Co. plant, Cloquet.

FIG. 8. Slate beds dipping south with nearly vertical flow and fracture cleavage, the latter emphasized by weathering. Recreation field, Carlton.

tabulation. These observations were made in the main area of outcrop between Atkinson and Cloquet. The steeply dipping cleavage is important in connection with inferences as to the general structure and estimates of thickness of the beds com-

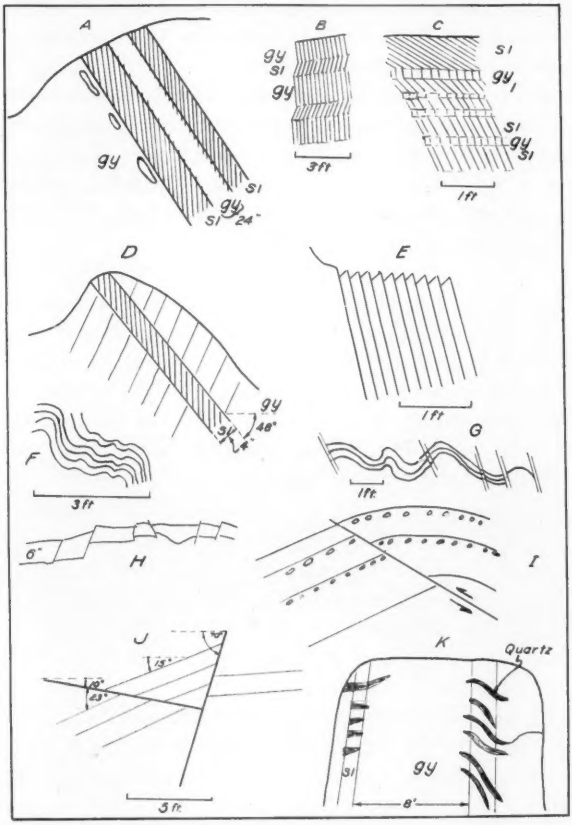

FIG. 9. Sketches of structures of the Thomson formation. *A*. Cleavage in slaty bed dies out in graywacke bed. *B*. Variation in angle of slaty cleavage between slate and graywacke beds. *C*. Extreme variation in angle of cleavage between slate and graywacke. *D*. Slaty cleavage inclined at acute angle to the bedding. Fracture cleavage or joints in graywacke. *E*. Slaty cleavage with fracture cleavage at surface giving a sawtooth effect. *F*. Trace of folded cleavage on joint face. *G*. Shear planes across much folded beds. *H*. Faulting in 6-inch graywacke bed interbedded with slate. *I*. Small fault with displacement indicated by concretions. *J*. Cross-section of faulting in St. Louis River gorge. *K*. Quartz veins in gash joints in slate beds.

prising the Thomson formation. It indicates that overturned folds are absent and isoclinal folds are possible only where cleavage and bedding are parallel.

Inasmuch as the most common dip of the beds is to the south, the dip of the slaty cleavage is generally either nearly vertical, or steeply south, with a nearly east-west strike (Fig. 8). This relation is, in a large measure, the result of shearing concentrated in the slate beds between massive graywacke beds, thus aiding in the development of the slaty cleavage.

The cleavage, which is well developed in the slate, in places was also observed to extend into the graywacke beds for an inch or two. Such an example is shown in Fig. 9 *A*. Where the cleavage extends into the graywacke slate or graywacke, it generally shows a sharp change in angle, having been less affected by the rotation due to shear (Fig. 9, *B* and *C*). The cleavage may be absent from the graywacke, and instead there are joints probably formed by the same shearing stress (Fig. 9 *D*).

The divergence of the dip of the cleavage in graywacke and in slate may amount to many degrees. In the channels of the St. Louis River along the north side of Cloquet, there is an extreme example of divergence; the beds of graywacke-slate and slate both dip 60° S, and the cleavage in the slate dips 83° S, that in the graywacke dips 60° N, a divergence of 37°. Divergences between 10 and 20 degrees are common.

It was noted that the cleavage planes are generally approximately parallel to the axial planes of minor folds. In these examples it is evident that the cleavage is independent of the bedding.

Fracture Cleavage.

Fracture cleavage that merges into closely spaced jointing is abundant in the Thomson slate beds and brings up forcibly the question of what should be called fracture cleavage and what should be referred to simply as closely spaced joints. In a sense the question is academic inasmuch as both joints and fracture cleavage represent fracturing. However, as Dr. Leith pointed

out to the writer, fracture cleavage refers especially to closely spaced incipient joints rather than necessarily to the joints themselves. Dr. Leith also points out the necessity for close spacing, thus emphasizing the parallelism of the planes.

With this limitation in mind only those examples of fractures that are closely spaced and decidedly regular are discussed under the heading of fracture cleavage.

The detailed work that has been done on the formation indicates strongly that the extreme development of fracture cleavage is partly a result of a later period of mild deformation that affected the formation, perhaps long after the development of the flow cleavage. Evidence of this later deformation includes faulting, minor shear zones, folding of cleavage, and fracture cleavage.

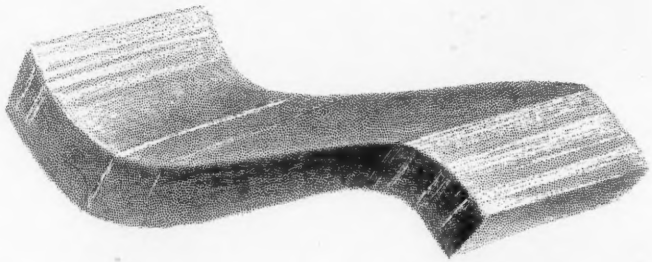

FIG. 10. Folded cleavage block of slate. Bedding is nearly at right angles to flow cleavage surfaces. Ends and sides of block are fracture cleavage planes.

There are many examples of cleavage blocks that were folded with apparent simultaneous development of fracture cleavage. In Fig. 10, for example, the principal folded plane is the flow cleavage, bedding is represented by the cross lines, and fracture cleavage planes by both the end and side fractures of the block. The end fractures happen to coincide with the bedding. In this and in other examples the original bedding has no effect on the later deformation.

Fig. 11 represents a common type of fracture cleavage block. The flow cleavage is shown as horizontal with the bedding dipping to the right. Both end and side faces are fracture cleavage surfaces of a somewhat rhombic block. Rhombic blocks of many sizes are common and in fact make up large parts of some slaty outcrops. Blocks of this type are well shown in exposures just south of the Northern Pacific railway station in Carlton.

Washboard-like surfaces in places result from fracture cleavage at an angle to slaty cleavage. A joint face in a railroad cut furnished a cross section of such an example (Fig. 9 *E*).

The curving of fracture cleavage planes where formed by differential movement between beds has been emphasized in many examples described by other writers. Curving seems to be the

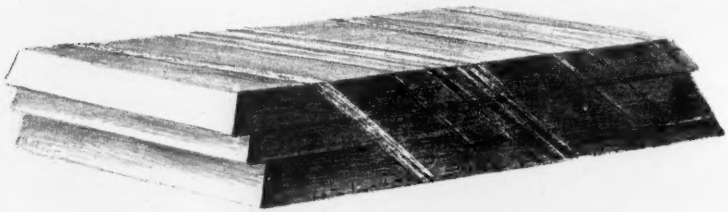

FIG. 11. Cleavage block of Thomson slate. Bedding inclined to the right, slaty cleavage planes are horizontal, end and sides are inclined fracture cleavage planes or joint planes.

exception rather than the rule in the fracture cleavage in the Thomson beds, although good examples were observed. S-shaped curving is frequently found in slaty cleavage of thin slate beds between competent graywacke beds. In some cases the S-shaped cleavage suggests a deformation after the development of the flow cleavage, perhaps during the later mild deformation that affected the region.

Many outcrops show closely spaced fractures parallel to the flow cleavage, which are emphasized by weathering (Fig. 8). Examination of many examples of this kind suggests to the writer that this is in reality a variety of fracture cleavage developed

along certain flow cleavage planes. The question naturally arises as to why these should be referred to as fracture cleavage. The answer is that they are actually fractures but they are spaced a visible distance apart, whereas flow cleavage planes are almost infinitely closely spaced. That is, fracture planes formed only along certain of the slaty cleavage planes where these were subject to later shearing between more competent beds.

Joints.

The Thomson formation is characterized by extensive jointing. Most large exposures show not only several planes of jointing forming sets and systems (Fig. 12), but also jointing of several

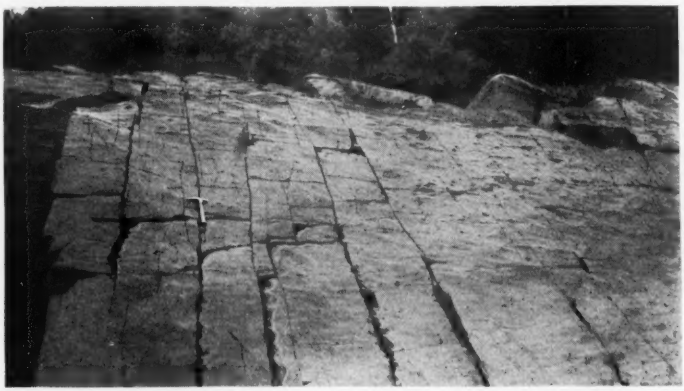

FIG. 12. Joints intersecting a bedding plane of graywacke. St. Louis River valley.

distinct sizes in the same rocks. The smaller joint planes are closely spaced and grade into fracture cleavage. The larger joints are very well defined (Fig. 12) and may be traced for hundreds of feet in exceptional cases.

The joints have rather consistent orientation in parallel sets in individual outcrops, and some sets seem to be repeated over wide

areas, but there is too much variation to work out more than general sets.

The dips and strikes of a large number of joints are plotted in Fig. 13. This shows that by far the greater number strike

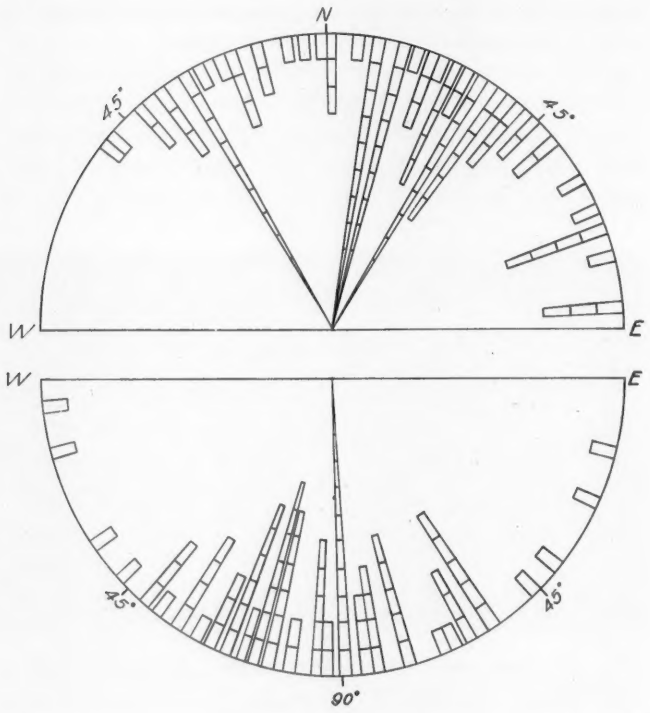

FIG. 13. The upper hemisphere shows the strike of joints and the lower Hemisphere shows the dip. The number of observations is shown by the number of blocks.

within 40 degrees of north and south. The dips are mostly steeper than 45 degrees. There is a noticeable concentration of strikes at about N 30° E, and of dips from vertical to 60° W.

It is noteworthy that most of the joints are either cross or transverse with respect to the strike of the beds and of the slaty cleavage—normal to the linear structure on axes of folds. In the case of joints which may have been formed by later deformation it is not necessary that the stresses were such that only cross or transverse joints were formed, but rather that bedding planes and flow cleavage planes relieved stresses in their direction and thus in reality played the role of joints in relieving the stress. It probably would lead to erroneous conclusions to work out any system of stress based purely on the joints in this area.

In general, the massive graywacke beds are cut by rather large continuous joints that are widely spaced. Commonly minor and less regular joints occur between the master joints. Only the master joints were considered important in the regional structure. Many slate beds are cut by a series of smaller joints, giving a blocky aspect to the exposures. In these, the flow cleavage planes always play the role of joints. As a rule, the bedding is unimportant.

Faults.

Recognizable faults are not common in the Thomson area, but the lack of good horizon markers makes it possible that small faults escape discovery and the large amount of covered area makes it certain that many zones of shearing might be masked by surficial deposits. In spite of the handicaps certain faults have been mapped. These fall into a natural classification as major and minor faults. The major faults were recognized mainly by the aid of aerial photographs in the region of numerous outcrops along the St. Louis River. These show that prominent strike ridges end abruptly, and at places appear to be offset. The lack of definitely recognizable horizons, however, precludes the correlation of apparently offset ridges, at least with certainty. These faults are parallel to zones along which there are many diabase dikes. The diabase is more easily weathered than the slate and graywacke, and accordingly a depression or gap occurs where the faults and dikes cut the ridges. It is believed that the dikes

were intruded along pre-existing faults that formed a well-defined series striking approximately N 30° E. Not all of the gaps in the ridges are occupied by diabase dikes, for one of the most prominent gaps in the abundant exposures southeast of Carlton appeared to be simply a shear zone, and slate and graywacke beds could be traced practically across it.

Opposite the plant of the Northwest Paper Company in Cloquet, a heavily brecciated zone crops out on an islet in the river, about 20 by 30 feet across, with other masses along the east bank and in the water. The fault zone also shows at the bend in the river a few hundred feet to the north. It is probable that the course of the river there is largely determined by the fault, which has a generally north-south trend.

The minor faults are of various types and several are illustrated in Fig. 9. In places, relatively thin graywacke beds occur in a thicker slate series and the graywacke adjusted itself during deformation by minor step faulting such as shown in Fig. 9 *C*, where the 6-inch graywacke bed is offset repeatedly at intervals of a foot or even less.

Intersecting faults occur just beneath the Highway bridge over the St. Louis River near the west entrance to Jay Cooke Park, Fig. 9 *J*. A fault with low dip shows only a small offset in the beds but the intersecting steeper fault has a wide divergence in strike of the beds on the two sides.

Well-defined slickensided surfaces were observed at a few places, but further detail is lacking because of the cover of glacial drift.

Deformation Subsequent to the Main Deformation.

A later, mild, deformation has been referred to above at several places. A short summary of some of the evidences and results of this deformation is in order.

Folding.—One of the most obvious, as well as conclusive, evidences of later deformation is the folding of the flow cleavage planes. A gentle fold of this type has been described (Fig. 10).

An extreme example was noted in the channel of the St. Louis

River in the SE ¼ of section 10, T 48 N, R 16 W, where the cleavage planes have been contorted into a series of irregular folds. A diabase intrusive near by may have had much to do with this structure.

Near the east quarter corner of Section 20, T 48 N, R 17 W cleavage slabs are sharply folded in asymmetrical folds which pitch at an angle of 30° in a direction N 75° E. Folded cleavage is commonly best seen on a cross-joint surface where the trace of the cleavage is etched out by weathering. On a cliff facing a swamp in the SE ¼ NW ¼ Sec 19, T 49 N, R 16 W, a horizontal rock surface shows minutely folded cleavage forming an irregular structure. That such folding was developed much later than the cleavage seems evident. Along the east side of the St. Louis River similar structure was noted by Winchell.

Below the Northern Pacific railway bridge over the St. Louis at Thomson, slickenside surfaces were noted cutting across the slaty cleavage at an acute angle.

Along the south bank of the St. Louis River in the SW¼ Section 9, T 48 N, R 16 W, the beds have unusually low dips and the slaty cleavage likewise has a dip of only 20 degrees. The cleavage is curved and a series of folds pitch gently to the east (Fig. 2). It seems probable that the abnormally low dip of both bedding and cleavage is a result of secondary folding.

Shear or Fracture Cleavage Zones.—Many well defined narrow zones of shearing cross the other structures in the slate and form narrow zones of fracture cleavage, or offset the slaty cleavage. This shows only faintly on photographs, but such shear zones were observed to extend nearly horizontally across a joint face in a quarry in Thomson village; the bedding dips 58° S and the cleavage 85° S, whereas the later shear, which affects the flow cleavage, particularly, dips roughly 5° S. In many cases this seems to be a shear or offset in the flow cleavage, which opened the cleavage planes but probably developed few new fracture planes. It is thus a fracture cleavage developed from slaty cleavage by shear concentrated in a narrow zone, commonly from 1 to 3 inches wide.

This secondary shearing is well shown in the channels and abandoned quarries on the east side of the St. Louis River just below the Thomson dam. Freshly broken pieces show slickensides along the secondary planes and bent slaty cleavage. Numerous examples of this secondary localized shear were observed throughout the area of outcrops.

SUMMARY AND CONCLUSIONS.

1. The beds of the Thomson formation occur on the north limb of the Lake Superior geosyncline, but lie below and are in marked structural discordance with Animikie and Keweenawan formations involved in the geosynclinal structure.

2. A gentle deformation later than the main period of folding and metamorphism is clearly shown in many exposures. This may represent the geosynclinal deformation in Keweenawan time.

3. The Thomson formation has been compressed into a series of folds. Lack of outcrops at critical places and the absence of good horizon markers prevent the working out of the outline of all major folds, but observation of minor structures shows that the major-fold axes strike nearly east-west, are nearly symmetrical with moderate dips on the limbs. The pitch is gentle and predominantly to the east. Isoclinal and overturned folds occur only near the granite contact.

4. Slaty cleavage is highly developed in the slate beds and shows varying relation to the bedding, but is uniformly steeper in dip than the bedding.

5. There is commonly a considerable divergence in the dip of the cleavage in the slate and graywacke beds. In an extreme example one dips north, the other south and the divergence is 37 degrees.

6. Fracture cleavage is abundant in the slaty beds. Rhombic fracture cleavage or joint blocks are common. In some exposures fracture cleavage has formed along certain of the slaty cleavage planes. This is inferred to be a result of later shearing of the slate between massive graywacke beds.

7. Sets and systems of joints are conspicuous in most outcrops of the formation. A majority of joints strike either across or transverse to the strike of the beds and slaty cleavage. Dips are mainly steeper than 45°.

8. Known faults are not numerous, but a series of diabase dikes appear to occupy approximately vertical fault planes that strike about N. 30° E.

9. The Thomson formation furnishes excellent examples of:

(*a*) The relation of flow cleavage to bedding where relatively competent beds alternate.

(*b*) The parallelism in strike of cleavage and bedding, thus indicating the orientation of the fold axes mainly in an east-west direction.

(*c*) The angular relation of cleavage to bedding in units of varying competence.

(*d*) The fact the fracture cleavage in slate beds is more often directly related to the slaty cleavage than to the bedding.

(*e*) The value of the trace of bedding on cleavage in determining the pitch of folds.

10. The combined structural features, as well as the general structure of the formation, furnish strong evidence against the correlation of the formation with the Virginia slate of the Mesabi range. The structure favors classification of the formation as Lower Huronian or older. This in turn favors a different interpretation for a large covered area north of Cloquet, Minnesota. Geophysical studies are indicated as the next step in the solution of this problem.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
Nov. 21, 1941.

NOTES ON THE ORIGIN OF THE MANSFELD COPPER DEPOSITS.

CHARLES HENRY WHITE.[1]

ABSTRACT.

A brief outline of the structure of the region is followed by observations on conditions underground at the Wolf shaft at Eisleben in June 1932, which indicate that the deposits are epigenetic.

THE copper deposits of the Mansfeld district are confined chiefly to a thin bed of black bituminous Permian shale which varies in thickness from five inches or less to twenty inches, the average being about nine inches. The shale underlies an area of 7000 square miles, but only a small fraction of it is known to be mineralized. Fifty square miles have been worked out, and known reserves are estimated at ten square miles.

The mines in this district have been worked for 744 years and have produced upwards of a million and a half tons of copper. The ore as mined contains from 2.5 to 2.8 per cent copper, and the annual production is about 25,000 tons of the metal. Silver, lead, and zinc are also produced.

The structure in the vicinity of Mansfeld is an open syncline with axis gently rising toward the west. The distance on the surface between the outcrops of the north limb and those of the south limb is 15 miles. The dip toward the axis varies from five to ten degrees. The formation is broken by many faults which are roughly parallel to the axis of the syncline. The fractures are pre-mineral, but there has been conspicuous post-mineral displacement.

My personal observations have been limited to the district around Eisleben and underground at the Wolf shaft. This shaft

[1] Presented before the Society of Economic Geologists at a joint session with the Geological Society of America, Boston Meeting, December 29–31, 1941.

at the time of my visit (June 1932) was 557 meters deep. It is vertical, and at a considerable depth below the surface it passes through the copper shale and continues well below into the underlying sandy conglomerate. From the station at the bottom of the shaft a horizontal drive provides a haulage way in the footwall to the ore bed—the copper shale.

The shale at this point is twelve inches thick and dips at six degrees from the horizontal. The pebbles in the underlying sandy conglomerate are nearly all white quartz as large as three inches in diameter but mostly smaller, and grade down in size toward the top to a coarse sand with grains from one-tenth to one-twentieth of an inch thick. There are also a few pebbles of black chert and jasper. The sandy beds immediately below the copper shale to a depth of from two to five feet are white—the Weissliegende, and below that they are stained faintly red with iron-oxide—the Rotliegende. The Weissliegende appears to be an integral part of the Rotliegende with a gradual reduction in size of grain toward the top and a rather abrupt loss of color that does not conform to planes of deposition or to cross-bedding, which is common.

The transition from white sands to the copper shale is abrupt, and in some places movement appears to have taken place on the contact. Going down the dip, the shale gradually thins down to an inch or less, and in some places where the bed is thin, copper mineralization extends down into the white sand a foot or so. The copper shale merges gradually upward into a dark impure limestone several feet thick. Where the overlying limestone has a red color the shale beneath it is barren of copper.

Farther down the dip the formations are cut off by a fault; a block several hundred feet wide has been dropped down about 60 feet; beyond the second fault the copper shale is found in its normal position. Crushed copper shale carrying ore has been dragged down along the faults. Near the faults are many small gash-like fissures a meter or so in length and a few centimeters wide filled with calcite and possibly some gypsum—a post-ore deposit. There are many faults in the district but mostly of small

throw, from two inches to two feet, rarely 150 to 300 feet. They are commonly short, parallel, and close together.

The chief ore minerals are bornite and chalcocite, the former predominating. Chalcopyrite and pyrite are also present, having been introduced later. The ore is not evenly distributed throughout the bed. It is more concentrated near the base and near the faults; away from the faults the bed is often much leaner. The ore minerals occur in minute particles irregularly disseminated throughout the shale or concentrated in streaks, generally parallel with the bedding. It also occurs in small nodules or concretions immediately under the shale in the sandstone and in the impure limestone above. Veins intersecting the shale and the underlying sandstone carry the nickel arsenides—niccolite, chloanthite, and maucherite with chalcopyrite, molybdenite, and uraninite. Zinc and lead sulphides occur in the upper part of the shale. The ores also carry small amounts of gold, silver, platinum, and vanadium.

Geologists from the early adolescence of the science have discussed the origin of the Mansfeld deposits. In 1756 Lehmann suggested that the copper was deposited in sea water with the shale and is, therefore, syngenetic. A majority of the geologists who have studied the deposits since have concurred in his opinion. Among these are B. von Cotta, von Groddeck, Steltzner, Bergeat, Lindgren, Pompeckj, Johannes Walther, Schneiderhöhn, R. Lang, R. H. Rastall, P. D. Trask,[2] and J. W. Gregory.[3] The operating staff of the mine at the time of my visit also held this view.

In 1889 Beyschlag advanced the theory that the ores at Kamsdorf had their origin in the adjacent Permian eruptive rocks. He believed that the copper was leached from the eruptive and was carried in solution up the faults whence it spread through the shale where it was reduced by the bituminous matter. In 1893 Pošepny advocated this idea for Mansfeld, and it was adopted by Henry Louis, Beck, S. F. Emmons, J. E. Spurr, and Krusch and Vogt (1921) but later (1929) Krusch changed to the syngenetic theory.

[2] Trask, P. D.: Econ. Geol., 20: 746, 1925.

[3] Gregory, J. W.: Inst. Min. & Met., London, Dec., 1930.

It is not my purpose in these notes to weigh all the evidence for and against the two theories but merely to record my observations and their implications with respect to the origin of the deposits.

1. The concentration of ore near the base of the shale and near the faults suggests that the ore came from beneath the shale and entered it along the faults.

2. The leaching agent that removed the iron from the sand beneath the shale apparently was guided by the lower surface of the shale as it moved up the dip.

3. The Weissliegende were no doubt originally Rotliegende since the bleaching cuts indiscriminately through cross-bedding and other structures without reference to bedding planes.

4. The occurrence of red areas in the overlying calcareous beds where the shale is barren suggests that at those points the copper-bearing fluid found no opening by which it could enter the shale and pass through it to reduce the iron oxide in the overlying bed.

5. Ore in the sandstone beneath the shale where the latter is thin indicates that the ore is not syngenetic with the shale; neither could the ore in the cross fractures in the shale be syngenetic.

The chief stumbling block of the epigeneticists has been their inability to point directly to a magmatic source. But this is true of many copper deposits and there is much evidence that the relation between intrusives and ore deposits is more often tectonic than genetic. I am inclined to believe that the ore fluids at Mansfeld came from great depths through the east-west fractures into the underlying porous sandstone and moved up the dip under the bituminous shale, reducing the iron oxide in the sandstone and dissolving it; that the solution passed into the shale, especially where it was fractured, and deposited the sulphides in the strongly reducing environment. The east-west veins in the Harz mountains west of Mansfeld were probably contemporaneous and cogenetic. Bateman gives a similar explanation for the formation of hypogene chalcocite at the Bristol mine in Connecticut.[4]

There were apparently two periods of mineralization at Mansfeld; the first introduced bornite and chalcocite; and the second,

[4] Bateman, Alan M., ECON. GEOL., 18: 122–166, 1923.

arsenides of nickel and cobalt, chalcopyrite, pyrite, and other minor minerals. In its vast extent the copper shale of Mansfeld is not unlike the copper-bearing beds of Northern Rhodesia and of the Upper Peninsula of Michigan, but the porosity of the Rhodesian and Michigan formations permitted the movement of fluids through them, whereas at Mansfeld the porous bed lies immediately under the precipitating bed. That metallic copper was not precipitated in the Mansfeld sandstone as it was in the Michigan conglomerate may be due to the small amount of iron oxide in the Rotliegende which was overwhelmed by the strongly reducing hypogene fluids, whose temperature was probably too low to permit reaction with the silica.

Gregory, advocating a syngenetic origin, writes "The assortment of metals is not surprising in a sedimentary ore, but not the assembly of metals that would be expected to be derived from one eruptive magma." The evidence is clear that there were two periods of mineralization; the first, apparently, a normal hypogene fluid carrying bornite and chalcocite; and the second, similar to that which was responsible for the Sudbury (Canada) deposits. The second necessarily could not be syngenetic and the evidence apparently turns the scale in favor of an epigenetic origin for the first also.

For the privilege of making this study I am indebted to the officials and operating staff of the company at Eisleben who afforded me every facility, and who generously presented me with choice specimens from the copper shale, including the nickel arsenides, native silver, and a well preserved fossil fish *Palaeoniscus freieslebeni Blainville*.

San Francisco, Cal.,
Dec. 1, 1941.

LÖLLINGITE FROM THE PHILIPPINE ISLANDS.

JOSEPH MURDOCH AND DION L. GARDNER.

ABSTRACT.

The rare mineral löllingite has been identified as the principal metallic gangue mineral of an important part of the ore in the San Mauricio mine, Paracale Mining District, Philippine Islands. Its relationship to the other ore minerals is described, and its crystallography briefly discussed.

LÖLLINGITE is ordinarily a rather rare mineral, occurring in limited quantity in relatively few localities, so that its occurrence as the principal metallic gangue of a large ore body may be considered worthy of description.

GEOLOGIC OCCURRENCE.

In the San Mauricio Mine, Paracale mining district, Philippine Islands, löllingite was first found in 1939 and designated as mineral "X" by the geological and chemical staffs of the mine. Identification was hampered by the fact that the material was extremely fine grained, without definite crystal form, and intimately intergrown, as seen later, with a number of other metallic minerals. Its occurrence is mentioned in a brief account of the geology of San Mauricio, which has appeared recently,[1] although at that time its composition was believed to be complex.

The löllingite occurs in the northern section of the Tacoma ore shoot, which lies in part of the San Mauricio-Tacoma vein system. This vein system is found as a mineralized north-trending zone of cross joints at the western end of the Paracale-Mambulas granite stock. In this zone, gold ore occurs in definite shoots, localized in the granite beneath a cover of incompetent serpentine and serpentinite.

[1] Barr, H. L., and Gardner, D. L.: The San Mauricio Mining Co., Jose Panganiban, Camarines Norte, P. I., A. I. M. E. Tech. Pub. 1187: 6–19, 1940.

Löllingite is common and locally abundant in the ore from the 300- and 400-level stopes at the northern extention of the Tacoma ore shoot, particularly as a stockwork in the hanging wall of the main vein. It also occurs in the contact ore, and in the main vein itself. Its distribution relative to the mineralization is shown in Fig. 1.

Ore and löllingite are associated, evidently as a late surge of the mineralization, following and distinct from the more widespread Tacoma mineralization. Ore from this section consists of intensely silicified granite cut by an irregular network of veins and veinlets, which contain the ore minerals. The silicification occurred in the early stages of mineralization, and apparently this portion of the vein was not opened to an appreciable extent during the period of the Tacoma mineralization that occurred further south. At a late stage the silicified granite was fractured, and the openings filled with the löllingite assemblage, which consists mainly of fine-grained löllingite, with a few patches of sphalerite, and minor amounts of galena, argentite (?), stephanite, native silver (or electrum), and arsenopyrite. The nonmetallic minerals are quartz and mangano-calcite, with the latter in much less abundance. Elsewhere along the vein, löllingite has not been found, and the wall rock alteration and mineralization are of an entirely different character.

PARAGENESIS.

Study of polished sections shows that löllingite and quartz were formed early, and continued to be deposited for a considerable time, in some places completely filling the available openings, and in others leaving open vugs mostly filled with later calcite. Of the associated metallic minerals, the sequence seems to be: sphalerite, galena, argentite and stephanite, arsenopyrite and then native silver. There seems to be in general little evidence of replacement of earlier by later minerals, although there is a ragged microscopic intergrowth of löllingite and argentite (?) which might indicate such a relationship. Other than this, these minerals always appear to be moulded about, or fill spaces between,

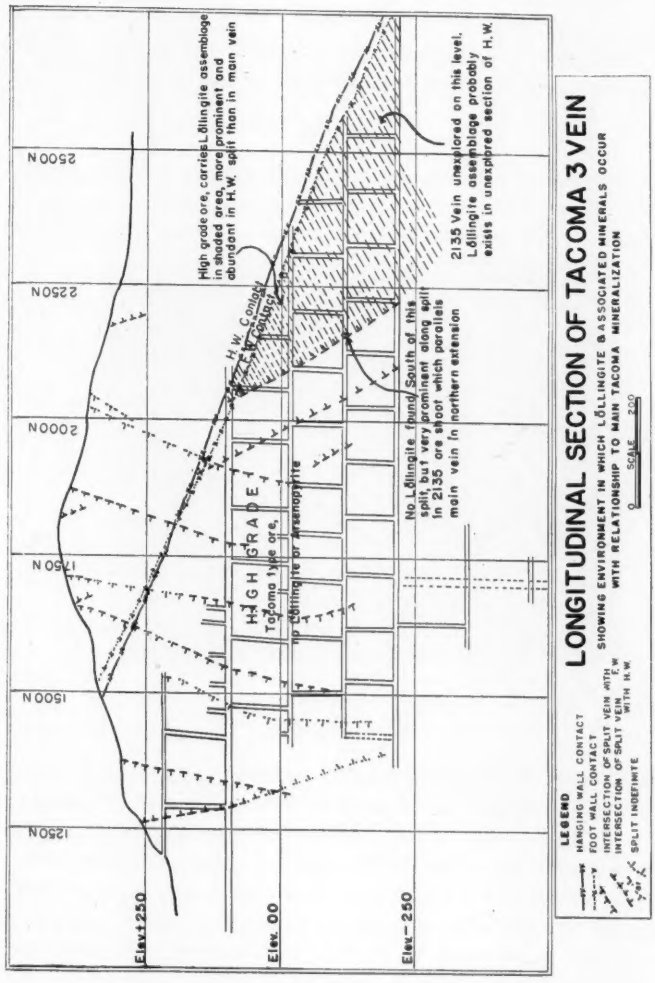
LONGITUDINAL SECTION OF TACOMA 3 VEIN
SHOWING ENVIRONMENT IN WHICH LÖLLINGITE & ASSOCIATED MINERALS OCCUR WITH RELATIONSHIP TO MAIN TACOMA MINERALIZATION
SCALE 200
LEGEND
HANGING WALL CONTACT
FOOT WALL CONTACT
INTERSECTION OF SPLIT VEIN WITH F.W
INTERSECTION OF SPLIT VEIN WITH H.W
SPLIT INDEFINITE
H.W. Contact
F.W. Contact
HIGH GRADE
Tacoma type ore,
no Löllingite or Arsenopyrite
High grade ore, carrieLÖllingite assemblage in shaded area, more prominent and abundant in H.W. split than in main vein
No Löllingite found South of this split but very prominent along split in 2135 ore shoot which parallels main vein in northern extension
2135 Vein unexplored on this level. Löllingite assemblage probably exists in unexplored section of H.W.
Elev+250
Elev. 00
Elev—250
12500N
15000N
17500N
20000N
22500N
25000N

FIG 1

idiomorphic grains of löllingite. Argentite and stephanite were not seen in contact with each other. In general, calcite is the last to form although some of the sulphides (not löllingite) occur as stringers between and around grains of this mineral.

MINERALS.

Löllingite.—This may occur as a fine grained, massive aggregate, intergrown with quartz, but is much more commonly in definite crystalline grains. These grains are small, 2 mm or less

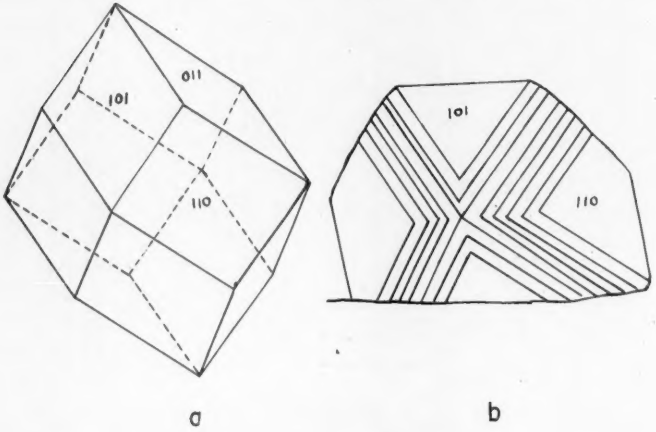

FIG 2

across, and are almost invariably flattened perpendicular to *a*, generally wafer-like in thinness, and show a narrow diamond-shaped cross section on the polished surface. Fig. 3 shows the typical appearance of the better crystallized löllingite, where it was free to develop in an open space later filled with calcite. Few separate crystals were found in the ore, but by dissolving away the calcite, many crusts of crystals were exposed. Most of the crystals are attached by one edge, so that they stand up on the surface. Further, the faces on one side are generally better developed than on the other, so that the flakes look lopsided. They

are marked by numerous striations parallel to the edges between prisms and macrodome faces. A typical habit of these thin flake-like crystals is shown in Fig. 2b. A few stouter tabular crystals permitted measurement of their forms with reasonable accuracy (figure 2a). Their habit is very like that of the löllingite crystals from Franklin, described by Bauer and Berman,[2] but without the pyramid faces. Only a few crystals gave good goniometric measurements, with values for the faces corresponding closely with those of Bauer and Berman. The forms are,

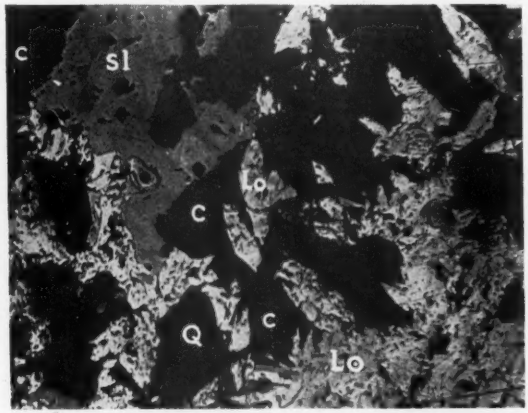

FIG. 3. × 50. Lo = löllingite. c = calcite. sl = sphalerite. Q = quartz.

m (110), *e* (101), *l* (011), with *l* missing from most of the thinner crystals. The *l* faces are generally marked by crevices, which indicate the incomplete junction of several individuals.

Etch reactions are somewhat different from those for löllingite as recorded in the various tables,[3] and led to the original supposi-

[2] Bauer, L. H., and Berman, H.: Löllingite from Franklin, New Jersey. Am. Min., 12: 39–43, 1927.

[3] Murdoch, J.: Microscopical Determination of the Opaque Minerals. New York, 1916. P. 84. Farnham, C. M.: Determination of the Opaque Minerals. New York, 1931. P. 86. Short, M. N.: Microscopic determination of the ore minerals. U. S. Geol. Surv. Bull. 914: 161, 1940.

tion that the mineral was new. The comparative results are indicated below:

	HNO_3	Aqua Regia
Murdoch	Faint brown	Slowly effervesces, very slowly turns faint brown.
Farnham	Coating of minute octahedral crystals, fumes tarnish, very slow coloring of surface	Neg.
Short	Slow effervescence and gray stain	Neg.
Paracale	Slowly brown and iridescent, no effervescence	Rapidly effervesces and tarnishes.

These differences are probably due to the variation in composition, as an analysis of selected crystals from Paracale, the only impurity being quartz, gave the following composition, calculated quartz free:

As 67.64, Sb 0.11, S 1.08, Fe 29.31, Cu 1.86. Spectroscopic traces only of Co, Pb, Mn (F. A. Gonyer, analyst). Microscopic examination shows that definite crystals are perfectly homogeneous, so that this analysis represents accurately the composition of this mineral.

Polarization colors are very pale-slaty blue, through pale brown to bright-orange yellow, depending on orientation.

A definitely single crystal was X-rayed by the oscillation method, and the cell size as determined by this means checked closely with the established values.[4] Accordingly, in spite of the differences in etch-reactions and general habit, the identification of the mineral is confirmed as löllingite. Specific gravity, determined on pure crystals and fragments, gave an average value of 6.9.

Arsenopyrite was not observed on the polished surfaces, but in the hand specimens, it generally occurs as minute, well developed, short prismatic crystals on the surface of open crevices, or partially embedded in calcite or quartz. It is most abundant where löllingite is absent, but may occur in isolated crystals among the flaky plates of the latter. The habit is prismatic parallel to *c*,

[4] Buerger, M. J.: The crystal structure of löllingite. Zeitsch. f. Kryst., Min., etc., 82: 165, 1932.

with the following forms present *m* (110), *q* (011), and a number of indeterminate faces in the brachydome zone, approaching (012), (013).

Sphalerite is irregularly distributed in the löllingite zone, in places in large irregular patches, and more uniformly as microscopic areas in the ore, commonly closely associated with galena.

Galena occurs in a few small areas, moulded around sphalerite grains, or as veinlets or patches in calcite; it may occur in the same area with argentite.

Native silver is most commonly in stringers or small patches of microscopic size distributed abundantly through some areas of the ore.

Argentite (?) occurs in small patches with galena, and in some of the specimens is intergrown with, and perhaps replaces, the massive löllingite.

Stephanite was not observed on the polished surfaces.

Quartz is abundant in all specimens, as formless clear grains scattered through löllingite, or as well formed drusy crystals on the walls of cavities. Some are younger and some are older than löllingite.

Calcite is apparently the latest mineral, and fills crystal-lined cavities in the ore minerals and quartz.

ACKNOWLEDGMENTS.

The analysis of löllingite was made possible by a grant from the Research Fund of the University of California. Dr. J. D. McCullough of the Chemistry Department, University of California at Los Angeles, was kind enough to make the X-ray photographs, and we are obliged to Marsman & Co., Inc., owners of the property for specimens, and permission to publish.

UNIVERSITY OF CALIFORNIA IN LOS ANGELES,
MARSMAN AND COMPANY, PHILIPPINES,
Sept. 22, 1941.

DISCUSSION AND COMMUNICATIONS

MECHANICAL POLISHING WITH A FILM OF ABRASIVE.

Sir:—J. Osborn Fuller's conception in ECONOMIC GEOLOGY, Vol. 36, pp. 199–211, of an abrasive film as an important factor in polishing ores on revolving lead laps, is one that will find ready acceptance. His experience, however, that too much abrasive or too much lubricant on the lead lap destroys the final perfect polish differs from mine. I find that a perfect polish is most readily and rapidly attained, both on sections of ore and mill products, when the specimen is rotating in a thick slurry of magnesium oxide and oil, as much, in fact, as can be retained on the lap during motion.

A likely explanation for this difference is the method of holding the specimen on the lap. If the specimen in contact with the polishing lap is under sufficient pressure, the conditions postulated by Fuller in his Figs. 4B and 5B cannot obtain. Excess abrasive and lubricant must be squeezed out, leaving only an abrasive film of uniform thickness between the specimen and the lap, provided, of course, that the grain size of the abrasive is uniform.

The polishing machine with which this experience has been gained is one that was built from the description of the original Vanderwilt machine. It differs from the original in two respects. The shaft of the upper revolving plate is set in fixed bearings and prevents the use of the head as a weight to hold the specimen in contact with the lap. The device employed for holding the specimen is one for which I was largely indebted to Mr. J. S. Mann, of the Department of Geology at the University of Melbourne, and is shown in the accompanying illustration.

The specimen is held against the surface of the lead lap by the pressure of a coil spring, transmitted through a steel spindle *A*, cupped at the bottom to fit a ¼ inch steel ball resting in the central cavity of the bakelite mount. The spring is placed in a cylindrical brass box *B* inserted in the head plate *C;* its lower end presses against a flange on the spindle and its upper end against a screw cap *D* on the brass cylinder. This pressure may be varied by screwing the cap up or down and is normally equivalent to about 10 lb. per sq. in. The actual amount does not seem to be im-

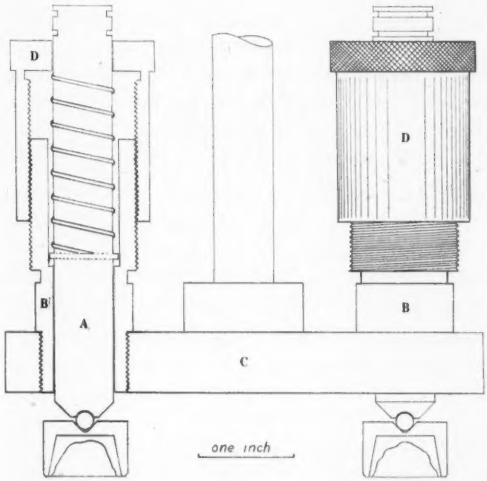

FIG. 1.

portant, but it must be sufficient to hold the specimen firmly, yet not too great to retard the spinning by friction. The specimen is inserted by lifting the spindle against the spring with a key that fits the slot at its upper end and then lowering it gradually on the steel ball. The pressure is thus centrally applied, and the flexibility of the ball joint maintains its even application. The steel ball was first introduced to prevent the tilting of the specimen and its attendant damage to the surface of the lead lap, and proved

itself a practical improvement on the conical contact employed by Vanderwilt. Whenever tilting now occurs, it is usually a sign that the lead lap is worn and needs re-surfacing.

The abrasive film does not operate as effectively immediately after the lap has been cleaned. It appears to be most effective after a certain amount of magnesium oxide is fixed on the surface of the lap. Fuller states that magnesium oxide (Merck & Co.) is used in his final polishing. This would appear to be the pure chemical reagent which, in my experience, is not suitable as a polishing powder. Calcined magnesia, as manufactured by the Washington Chemical Co., England, is, however, eminently satisfactory and requires no treatment before use.

This device has largely contributed to the successful operation of the machine which has been in use for about ten years with two lead laps, one for use with graded 303½ optical emery and one for use with magnesium oxide. "Dishing" of the lead laps occurs, as in the experience of others, but this is countered periodically by re-surfacing the lap in a lathe. The machine is retained for polishing only. The preliminary grinding is carried out on bronze and zinc laps used in the preparation of rock sections.

The excessive use of abrasive and lubricant applies only to the lap with magnesium oxide. Very economical use is made with the graded 303½ optical emery in the polishing stage preceding the use of the magnesium oxide.

F. L. STILLWELL.

UNIVERSITY OF MELBOURNE,
July 14, 1941.

REVIEWS*

Initiation à la Géologie. By J. W. Laverdière and Léo G. Morin. Pp. 158; Figs. 176. Editions Fides, Montreal, 1941. Price, $1.00.

This elementary textbook was written to modernize the ideas of older textbooks of geology published in French Canada, and to replace those published in France, which were mostly concerned with European geology. The book is finely illustrated, well written and carefully organized for the use of high-school students. It contains abundant photographic documentation on Eastern Canada and more especially the Province of Quebec. That alone would suffice to recommend it to anybody interested in geology. In geomorphology the section on the work of water is strikingly good. The chapters on stratigraphy make special reference to the formations of the Province of Quebec, duly situated in their proper North American setting. The book ends with a review of glaciation.

The shortcoming of such a book is that of any elementary text which has to cover so wide a field. For instance, metamorphism, which needs many pages of explanation to be really understood by beginners, is only briefly mentioned in this book.

The price is low, yet this is no cheap book. With its good paper, fine illustrations, excellent printing, and altogether artistic presentation, it should be a valuable addition to any library.

P. E. Auger.

The Soils That Support Us. By C. E. Kellog. Pp. 370; Figs. 79. Macmillan Co., New York, 1941. Price, $3.50.

This popular book relates to soils, their cultivation, their products, and their effect upon people. Eighteen chapters cover the materials of soils, the soils of grasslands, deserts, forest lands, their uses, and their response to care, ploughing, fertilizers, and rain. Particular attention is given to their effect upon individuals and groups of people.

Dynamic Meteorology. By Bernhard Haurwitz. Pp. 365; Figs. 89. McGraw-Hill Book Co., New York, 1941. Price, $4.00.

This is a technical book that deals with the fundamentals of meteorology and treats of the appreciation of the laws of thermodynamics and hydro-

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, W. S. Bayley, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

dynamics to the atmosphere and its motions. Eighteen chapters deal with the Earth, Atmospheric Status, Condensation, Radiation, Motions, Pressure Fields, Turbulence, Circulation, Energy and Air Masses, Fronts, Cyclones, and Anticyclones. The material is fundamental and is largely a mathematical treatment.

The West Highlands and the Hebrides. By ALFRED HARKER. Pp. 127; Figs. 81. Cambridge Press, Cambridge, England, 1941.

This book is called a geologist's guide for amateurs. It is an unfinished manuscript by the later Professor Harker brought to publication by the aid of Sir Albert Seward, Professor C. E. Tilley, and Dr. J. E. Richey. Professor Harker's delightful sketches are included. The book is a story of the geology of these regions that one would encounter afoot or afloat and is told in simple language for the traveller. Nevertheless, as might be expected from so profound a student of geology as Harker, there is also much of interest to the advanced geologist.

Photomicrography. By R. M. ALLEN. Pp. 365; Pls. 50. Van Nostrand Co., New York, 1941. Price, $5.50.

Such a timely volume is almost a necessity to users of the microscope, both research and commercial. Its contents should be helpful not only to the beginner but to the specialist and the beginner cannot afford to be without it. Its eight chapters deal with fundamental principles, modern equipment, homemade equipment, technique, special processes, microphotography, accessories, and illustrations. The illustrations are excellent.

Oil Well Drainage. By STANLEY C. HEROLD. Pp. 407. Stanford Univ. Press, Stanford Univ., Cal., 1942. Price, $5.00.

This is a practical book, from which the author has shed his deep mathematical treatment of former writings and presents the subject in readable style for geologists, engineers, landowners and operators. It deals with reservoirs, the function of gas, drainage, effect of stratigraphy and structure, and recovery. Pithy marginal notations present the context at a glance. Every geologist and operator should read it.

BOOKS RECEIVED.

WILLIAM E. BENSON.

Tungsten Resources of the Blue Wing District, Lemhi County, Idaho. E. CALLAGHAN AND D. M. LEMMON. Pp. 21; pls. 5; figs. 2; geol. map 15″ × 18″, scale 1 cm. = 250 ft. (app.). U. S. Geol. Surv., Bull. 931–A. Washington, 1941. Price, 30 cents.

Quicksilver Deposits in San Luis Obispo County and Southwestern Monterey County, California. E. B. ECKEL, R. G. YATES, AND A. E. GRANGER. Pp. 66; pls. 10; figs. 9; geol. map, scale 1:31,680. U. S. Geol. Surv., Bull. 922–R. Washington, 1941. Price, 75 cents.

Geology of Area Between Green and Colorado Rivers, Grand and San Juan Counties, Utah. E. T. MCKNIGHT. Pp. 144; pls. 13; figs. 3; geol. map in color, 36″ × 57″, scale, 1:62,500. U. S. Geol. Surv., Bull. 908. Washington, 1940. Price, $1.50.

Contributions to the Data on Theoretical Metallurgy: IX. The Entropies of Inorganic Substances, Revision of Data and Methods of Calculation. K. K. KELLEY. Pp. 97; tables 8. U. S. Bur. Mines, Bull. 434. Washington, 1941. Price, 15 cents.

Seismicity of the Earth. B. GUTENBERG AND C. F. RICHTER. Pp. 117; figs. 17; tables 22. Geol. Soc. America, Spec. Paper No. 34. New York, 1941. *Gives relative seismicity of various parts of earth and discusses geographical and geological relationships of principal zones of activity.*

Mineral Industry of the Northwest Territories. C. S. LORD. Pp. 136; figs. 9. Canada Dept. Mines and Resources, Geol. Surv. Memoir 230. Ottawa, 1941. Price, 50 cents. *General geography and geology of the region plus description of mining and milling operations of all important deposits. Includes general information valuable to present operators and future prospectors.*

Jacquet River and Tetagouche River Map-Areas, New Brunswick. F. J. ALCOCK. Pp. 43; pls. 2; 2 geol. maps in color, scale 1″ = 2 miles. Canada Dept. Mines and Resources, Geol. Surv. Memoir 227. Ottawa, 1941. Price, 25 cents. *Areal geology suggests possible mineral deposits which could only be detected by subsurface methods of prospecting.*

Geology of the Mafungabusi Gold Belt. A. M. MACGREGOR. Pp. 26; figs. 2; geol. map 8″ × 11″, scale 1″ = 4 miles. Southern Rhodesia Geol. Surv., Short Rept. No. 35. Salisbury, 1941. *Gold reefs occur in metamorphic rocks intruded by granites. Report describes principal mines of the region.*

Geology and Ores of the Boliden Deposit, Sweden. O. H. ÖDMAN. Pp. 181; pls. 48; figs. 28; tables 42. Sveriges Geol. Undersökning, Ser. C, No. 438. Stockholm, 1941. Price, 8 kronor. *Complete detailed account of chemistry, mineralogy, and theories of origin of the three types of ore in this important gold-copper deposit. The forty-eight plates include photomicrographs of thin and polished sections, and photographs of underground exposures.*

La Prospection Electrique du Sous-Sol. E. POLDINI. Pp. 94; figs. 39. Librarie F. Rouge & Cie. Lausanne, 1941. *A well written account of electrical prospecting by the use of continuous current methods. The writer first discusses the physical theories of the methods followed by sections illustrating their application to problems in civil engineering, tectonics, ground water study, and the search for metalliferous or petroliferous deposits. A valuable reference for all interested in subsurface methods.*

Carvão Mineral de Barra Bonita e Carvaõzinho. N. PASSOS, I. C. DO AMARAL AND OTHERS. Pp. 144; pls. 6; figs. 62; maps 13; numerous tables. Brazil Min. da Agric., Div. de Fom. da Prod. Min., Bol. No. 42. Rio de Janeiro, 1940. *A short section on the general geology followed by sections on the various coal basins of the area.*

Minerais Estrategicos. L. J. DE MORAES. Pp. 25; figs. 1; maps 4. Brazil Min. da Agric., Div. de Fom. da Prod. Min., Avulso No. 45. Rio de Janeiro, 1940. *A summary of the Brazilian deposits of minerals vital to the world.*

Geologia de Goiaz a Cuiabá. A. I. ERICHSEN AND A. LÖFGREN. Pp. 25; pls. 8; figs. 3; geol. map 4½″ × 4½″, scale, 1:1,000,000. Brazil Div. de Geol. e Min., Bol. 102. Rio de Janeiro, 1941. *Reconnaissance geology from traverses between and around Goiaz and Cuiabá. One page English summary gives very little of the actual contents of the paper.*

O Devoniano do Paraná e Geografia e Suas Relações com a Geologia. P. F. DE CARVALHO. Pp. 30; pls. 10; figs. 6; tables 1. Brazil Div. de Geol. e Min., Bol. No. 109. Rio de Janeiro, 1941. *Short paper on the stratigraphy and geology of the Devonian in Paraná followed by a more general paper on the relationship of geography and physiography to geology.*

Código de Taxionomia Estratigráfica. G. DE PAIVA. Pp. 28. Brazil Div. de Geol. e Min., Not. Prelim. e Estudos No. 21. Rio de Janeiro, 1940. *A translation of the well-known "Classification and Nomenclature of Rock Units," published by the G. S. A., vol. 44, 1933. The Brizilian geologists propose that it be adopted in all South American countries.*

Geologic Map of the State of Goiaz, Brazil. J. CASTIGLIONE AND A. J. DE MATOS MUSSO. In color, 27″ × 41″, scale 1:1,500,000. Brazil Div. de Geol. e Min. Rio de Janeiro, 1940.

Restingas Na Costa Do Brasil. A. R. LAMEGO. Pp. 76; figs. 48. Brazil Div. de Geol. e Min., Bol. No. 96. Rio de Janeiro, 1940. *Treats the genesis and evolution of the bars and dunes of the coast of Brazil.*

Metalurgia do Alumínio no Brasil. M. DA SILVA PINTO. Pp. 46; figs. 22; tables 8. Brazil Lab. da Prod. Min., Bol. 2, 1940. Rio de Janeiro, 1940. *Deals with the Brazilian bauxite deposits and the possibility of establishing a large aluminum industry in Brazil.*

Un Mineral do Grupo Ambligonita-Montebrasita, de Mogi' das Cruzes, São Paulo. A. N. DA CUNHA, O. COSTA, AND J. BORGES. Pp. 8; figs. 2. Brazil Div. de Geol. e Min., Not. Prelim. e Estudos No. 22. Rio de Janeiro, 1941. *A mineral, intermediate in composition between amblygonite and montebrasite occurs in considerable quantity in pegmatites near São Paulo.*

Les Gisements D'Or de la Région de Saint-Yrieix (Haute-Vienne, France). P. H. SEVENSMA. Pp. 115; pls. 4; figs. 47; numerous unnumbered tables. George & C^ie^ S. A., Libr. de l'Université. Geneva, 1941. *Geology and origin of several deposits of this region. Well written with good photomicrographs.*

Bauxite Resources of the United States. J. R. THOENEN AND E. R. BURCHARD. Pp. 42; figs. 1; tables 6. U. S. Bur. Mines Rept. Invest. 3598. Washington, 1941. *Summarizes all known bauxite deposits of U. S. On basis of present reserve estimates, our supply will only last 5.8 years if foreign imports are cut off.*

Carbonizing Properties and Petrographic Composition of Powellton-Bed Coal from Elk Creek No. 1 Mine, Emmett, Logan County, W. Va., and the Effect of Blending This Coal with Pocahontas No. 3 and No. 4-Bed Coals. J. D. DAVIS, D. A. REYNOLDS, G. C. SPRUNK, AND C. R. HOLMES. Pp. 45; figs. 25; tables 20. U. S. Bur. Mines, Tech. Paper 630. Washington, 1941. Price, 10 cents.

Carbonizing Properties and Petrographic Composition of No. 1-Bed Coal from Bell No. 1 Mine, Strugis, Crittenden County, Ky., and the Effect of Blending This Coal with Pocahontas No. 3 and No. 4-Bed Coals. J. D. DAVIS, D. A. REYNOLDS, R. E. BREWER, G. C. SPRUNK, AND L. D. SCHMIDT. Pp. 45; figs. 26; tables 22. U. S. Bur. Mines, Tech. Paper 628. Washington, 1941. Price, 10 cents. *Blending the coals improves the quality of the coke produced.*

Coal Paleobotany. R. THIESSEN AND G. C. SPRUNK. Pp. 56; figs. 44. U. S. Bur. Mines, Tech. Paper 631. Washington, 1941. Price, 15 cents. *A paper which summarizes much previous research work on coal textures and floras. It describes the various structures characteristic of the Paleozoic coals and the plants responsible for each type. Illustrations are very good.*

Publications on the Geology, Mineral Resources, and Mineral Industries of Illinois. Pp. 97; maps 2. Ill. Geol. Surv. Urbana, 1941. *An annotated bibliography of Illinois geology.*

Surface Structure Map of Shelby, Effingham, and Fayette Counties. W. A. NEWTON, J. M. WELLER, AND A. H. BELL. Pp. 15; figs. 2; tables 3; map 21″ × 25″, scale 1″ = 2 miles (app.). Ill. Geol. Surv., Rept. Invest. No. 76. Urbana, 1941. *Data largely from drill cores of the oil companies.*

Halliwell Mine Map-Area, Beauchastel Township, Temiscamingue County. G. S. MACKENZIE. Pp. 25; pls. 1; figs. 3; geol. map in color, scale 1″ = 800 ft. Quebec Bur. Mines, Geol. Rept. No. 7. Quebec, 1941. *General and economic geology. Gold ore of good grade found in Pre-Cambrian formations.*

Eustis-Mine Area, Ascot Township. G. V. DOUGLAS. Pp. 24; pls. 4; figs. 10; plans 1; geol. map in color, scale 1″ = 800 ft. Quebec Bur. Mines Geol. Rept. No. 8. Quebec, 1941. *Large pyritic ore bodies are mined for copper.*

Investigations of Methods and Equipment Used in Stream Gaging. C. H. PIERCE. U. S. Geol. Surv., W. S. P. 868. In two parts. Washington, 1941.

Part 1; 868–A. Performance of Current Meters in Water of Shallow Depth. Pp. 35; pls. 27; figs. 3. Price, 15 cents.

Part 2; 868–B. Intakes for Gage Wells. Pp. 38; pls. 4; figs. 6; tables 11. Price, 15 cents.

SOCIETY OF ECONOMIC GEOLOGISTS

Abstracts of Papers Presented at the Twenty-Second Annual Meeting in Conjunction with the Geological Society of America, Boston, Mass., December 29–31, 1941.

TIN DEPOSITS OF CARGUAICOLLO, BOLIVIA.

F. S. TURNEAURE AND RUSSELL GIBSON.

The Carguaicollo tin deposits are in the Department of Potosi about 20 kilometers east of Rio Marquez, a station on the Antofagasta-Bolivia Railway.

The veins contain tin with subordinate silver and are of interest because the principal ore mineral is teallite, a sulphide of tin and lead.

The host rock of the veins is a dacite porphyry intrusive cutting folded sedimentary rocks. At Carguaicollo, the intrusive is exposed at the surface for about seven square kilometers but surrounding this area the dacite is covered by nearly horizontal tuffs and lavas which contain no veins.

The most abundant tin mineral is teallite, but franckeite and cassiterite, also, are present. Wurtzite and sphalerite are abundant; pyrite and marcasite somewhat less common. The silver occurs mostly with sphalerite and wurtzite, though some is found with teallite. Other minerals present are galena, arsenopyrite, proustite, quartz, chalcedony, siderite and alunite.

On the basis of predominant sulphides present most of the veins may be divided into three groups: (1) teallite-wurtzite-sphalerite, (2) wurtzite-sphalerite-pyrite, and (3) pyrite-marcasite veins. Non-metallic minerals are distinctly subordinate.

Within the main zone most veins strike nearly north, but a few strike N. 40°–60° W. To the south the strike gradually changes to N. 20° E. The veins dip 45°–80° either easterly or westerly. The vein width averages 10–15 and rarely exceeds 50 centimeters. Though narrow some veins are rather persistent.

In the zone of oxidation the zinc is largely removed and the teallite veins are locally changed to a fine-grained mass of cassiterite, anglesite, jarosite, and limonite.

SCHEELITE DEPOSITS IN THE GREENHORN MOUNTAINS OF THE SOUTHERN SIERRAS.

NELSON C. DALE.

Scheelite deposits are found in and adjacent to the Greenhorn Mountain Park of the Sequoia National Forest of Kern County, California. More specifically, these deposits are found in the Cedar Creek Mining District, 52 miles east of Bakersfield, California, at elevations ranging from 5000 feet to 7000 feet above sea level. These geographic and topographic relations are best noted on the Tobias Peak Quadrangle.

Whether viewed by natural or ultraviolet light, scheelite appears crystalline with square prisms or anhedral grains as disseminations in a groundmass of garnet, epidote, amphibole, pyroxene, quartz, calcite, pyrite, pyrrhotite, and molybdenite.

Its occurrence is principally with the quartz-epidote and garnet zones of the contact metamorphic limestones of a great roof pendant intruded by granitic (Granodiorite-quartz-diorite) members of the Sierran batholith. To a lesser extent scheelite is found in quartz veins or lenses in the associated marble or in veins or fault fissures along with epidote and garnet in the quartzites associated with the metamorphosed limestones.

The WO_3 content appears to be greatest near the contact where .59 per cent and .42 per cent have been recorded at two places on the same body along the strike. Away from the contact the percentages of WO_3 were obviously less.

At the annual meeting of the Society held in conjunction with the G. S. A. at Boston, December 29–31, technical sessions were held the afternoon of December 30 and the morning of December 31. Abstracts of the papers presented appeared in the December number of this Journal. A well attended Society luncheon was held on December 30. W. H. Emmons, profssor of economic geology at the University of Minnesota, was named the Penrose Gold Medallist of the Society at the council meeting held on December 29. The presentation will take place at a dinner to be held in New York on the evening of February 10, at 7 P.M. in the Princeton Club, 39 E. 39th St., in conjunction with the meetings of the A. I. M. E.

W. D. Johnston, Jr., found it necessary to resign as Secretary of the Society because of his departure in January for Brazil, where he will be stationed for some time in connection with the Government program of assisting in the development of South American mineral resources. C. H. Behre, Jr., of Columbia University has been appointed Secretary of the Society to succeed Mr. Johnston.

The following officers were elected:

President-elect, W. B. Heroy
Vice President-elect, R. C. Allen
Regional Vice Presidents,
Ben Lightfoot, Africa
A. L. Coulson, Asia
F. L. Stillwell, Australia
R. H. Rastall, Europe
Manuel Santillan, North America
W. S. March, Jr., South America
Councillors, 1942–44,
A. I. Levorsen
J. A. Noble
Arthur Notman

The following new members were elected: G. L. Adair; James Boyd; R. D. Butler; Antonio Calvache; J. W. Feiss; D. F. Frasche; G. E. Goodspeed; A. L. Howland; O. H. Leonardos; V. M. Lopez; R. B. Miller; R. F. Munoz; V. E. Oppenheim; R. S. Poor; J. S. Stevenson; A. E. Sandberg; T. P. Thayer; G. L. Thornburg; O. C. Von Schlichten.

SCIENTIFIC NOTES AND NEWS

P. D. WILSON, Vice President of Pardners Mines Corporation, has been appointed Chief of Production of the Aluminum and Magnesium Branch of OPM, responsible for the production of bauxite, alumina, aluminum and magnesium, for all products fabricated therefrom and for the supply of all ingredients necessary for their production.

D. F. HEWETT, Chief of the Metalliferous Division of the U. S. Geological Survey, has left for Santiago, Chile, to attend the Pan-American Mining Congress.

The AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE held joint meetings in Dallas, Texas, December 29–31, with the GEOLOGICAL SOCIETY OF AMERICA, DALLAS PETROLEUM GEOLOGISTS, and the FORT WORTH GEOLOGICAL SOCIETY. Technical papers on Southwestern geology were presented on Monday, December 29th.

ALAN M. BATEMAN has been appointed Special Representative of Metals Reserve in conjunction with the State Department to make an economic survey of war minerals in Mexico, and to accelerate present production of mines and smelters and open up new mines in Mexico to speed the flow of urgently needed metals for the war program of the United States.

W. F. FOSHAG, DAVID GALLAGHER, CARL FRIES, JR., and DONALD E. WHITE will leave for Mexico shortly to make geological studies of mercury, tin and antimony deposits. This work is in cooperation with that of Mr. Bateman.

V. M. LOPEZ of the Servicio Tecnico de Geologia y Mineria at Caracas, Venezuela, has been made dean of the school of geology of the Universidad Central de Venezuela.

H. D. SMITH, Newmont Mining Co., H. T. HAMILTON, Treasurer of the A. I. M. E., and D. D. IRWIN, of the Pure Oil Co., Chicago, are on leave as advisers to Metals Reserve in Washington.

J. W. PEOPLES has returned from chromite work in Montana for the U. S. Geological Survey and will be on leave of absence from Wesleyan University at the Geological Survey for the rest of the academic year.

D. H. MCLAUGHLIN made a brief visit to the East during the New Year period.

M. W. HAYWARD has left for a month's trip to Colombia, South America.

Y. S. BONILLAS of Mexico City came up to Denver and to New York the latter part of January.